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Where you come from, and where you're going: attention and action in manual aiming

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Lay Summary of Thesis

Attention is a limited resource, which can be allocated in different ways to better perceive one's surroundings. Previous work has found that attention is allocated to the target of an upcoming movement, so as to aid its execution, whether the movement is performed by the eyes or a hand. This can be seen by improved identification of stimuli presented for a brief amount of time at the target location before the movement has been executed. Furthermore, previous research has also found that attention is allocated along the trajectory of a manual movement being executed, and also that attention is allocated to the area around one's body. One of the main aims of the initial experiments in the present thesis was to investigate whether attentional resources were also allocated to the starting location of a manual movement. We did this by comparing the amount of attention allocated to the target of the movement, the movement's starting point, the location of the stationary hand, and a location that was not pointed to. We found that the starting location did receive attentional resources, supporting the view that there is a bias to allocate attention to locations relevant to the movement. However, this competed with a bias to allocate attention to the area surrounding one's body, and task difficulty also influenced the way in which attention was allocated. For instance, the results from Experiment 5 suggest that in a more challenging task, with more potential movement targets to choose from, only the movement target received attentional resources. The final three experiments investigated whether we could replicate previous work which found that in multi-step pointing sequences, attention was allocated in parallel to all targets before the first movement was performed. We found that most of our participants found the perceptual task too difficult under these challenging circumstances, and only our final experiment found attentional enhancement at the first movement target, and some evidence for attentional enhancement at the target of the second pointing movement. Since our final, more challenging experiments had similar experimental parameters as previous work in the literature, this calls into question the generalisability of some previous work, and highlights the potential role that practice might play in these results. In conclusion, the present thesis found support for action planning being a factor in influencing the way attention is allocated, but the details depend on its interplay with other biasing factors and task parameters, such as the difficulty of the task.

Declaration

I hereby declare that this thesis is of my own composition, and that it contains no material previously submitted for the award of any other degree. The work reported in this thesis has been executed by myself, except where due acknowledgement is made in the text.

Signed,

Sebastián Sandoval Similä

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Abstract

The way we act upon the world influences our visual perception of it. For instance, previous work has found visual perceptual enhancement at the targets of upcoming saccades (e.g. Deubel & Schneider, 1996) and pointing movements (e.g. Deubel, Schneider, & Paprotta, 1998). Visual perceptual enhancement has also been found along the trajectories of manual movements (Festman, Adam, Pratt, & Fischer, 2013a, 2013b), but the area surrounding static hands have also been found to receive perceptual enhancement (Reed, Grubb, & Steele, 2006). The initial question addressed by the present thesis was whether the preparation of a manual movement would also induce perceptual enhancement at the effector location (i.e. the movement's start point). In other words, do people not only attend where they are going, but also where they are coming from? To address this question, the novel aspect of our task was that participants not only had to select the movement target, but also the moving hand.

Across the eight experiments of the present thesis we applied variations on a popular experimental task, asking our participants to conduct pointing movements and studying how this influenced their allocation of visuospatial attention. This was measured by recording whether they could successfully identify a discrimination target (DT), with the discrimination rates at different locations taken to index the amount of attention allocated there. Our first four experiments found evidence for enhancement at the starting point of a movement, but this effect was inconsistent and appeared to compete with other mechanisms for orienting attention. For example, our first experiment found enhancement only at the target location, which may have been induced by having used predictable locations for the DT, whereas Experiment 4 found only an enhancement at both hands, static and responding, which might have been due to the ability to plan the movements in advance. Since in each trial in Experiment 4 participants had to execute one movement out of only two possibilities, this may have allowed them to pre-program both movements before each trial and execute them from memory.

In Experiment 5 we increased the number of potential movement targets in order to increase the difficulty of target selection and reduce movement predictability, while also lowering the DT presentation times. Under this more challenging paradigm we found perceptual enhancement only at the movement target, but also that the perceptual task was too difficult for half of our participants. Did we fail to induce enhancement at multiple locations because of the specific task our participants were executing, or due to a general

inability to do so within this more challenging version of the experimental paradigm? To address this question we decided to test whether we could still induce perceptual enhancement at two locations within these experimental parameters, but attempting to replicate the work of Baldauf, Wolf and Deubel (2006). They had reported that carrying out pointing sequences resulted in parallel allocation of attention to all movement targets before movement onset. We repeatedly failed to find any enhancement at any location, even when we increased the presentation times to durations used in the earlier experiments.

In our final experiment we mounted a more direct replication of Baldauf et al (2006), and we also conducted a preliminary calibration stage in which we attempted to adjust the DT's presentation time to each participant's level of ability by assessing their perceptual performance. This calibration was only successful in a third of our participants, with the majority still finding the perceptual task too challenging within the range of exposure times used. Furthermore, even amongst those participants selected for their good perceptual performance in the calibration task, we found visual enhancement only at the first movement target during the two-step pointing sequence. This calls into question not only the general replicability of the work of Baldauf et al. (2006), but also Deubel et al. (1998).

On the whole, our findings suggest that although the pattern of attentional allocation is influenced by action planning, including the starting point of a movement, this is but one of many competing factors. Furthermore they call into question the general replicability of previous high-profile results, and call for a greater acknowledgement and investigation of the possible role of extensive practice in yielding some of the results found in the literature. The thesis concludes with suggestions for future work.

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Chapter 1: What is Visuospatial Attention?

1.1 Introduction

In order to successfully interact with the world, one needs to be aware of one's surroundings, whether in order to monitor for any potential dangers or other objects of interest. However, we are constantly being bombarded by different forms of sensory information, and it would require too much processing power to be able to focus on all of it simultaneously. How, then does the brain avoid being overloaded with information? This is where attention steps in, although the precise definition of attention itself is a difficult question that has been under debate for a long time.

Attention can essentially be seen as a mechanism which attempts to focus our processing resources on the incoming sensory information that is the most important at that point in time. Of it, William James said the following: "Everyone knows what attention is. It is the taking possession of the mind, in clear and vivid form, of one out of what may seem several simultaneously possible objects or trains of thoughts…It implies withdrawal from some things in order to deal effectively with others" (James, 1890, p. 403). Everyone might know what attention is, but even though this quote is over 100 years old, the intricacies of the mechanisms involved in attention are still hotly debated. Broadly speaking though, the broad definition of attention has changed little in the course of the century. What does it mean though, to 'deal effectively with things' at the expense of others? In the current literature attention is said to have had an effect in the form of decreased RTs for responding to certain stimuli, as well as enhanced discrimination of them (e.g. Posner, Snyder, & Davidson, 1980). In other words, attention to said stimuli improves the processing of them, whether it is in terms of detection or discrimination. Another critical point of the above quote concerns the "withdrawal from some things". This highlights that attention is a finite resource, and allocating attention to a certain stimulus results in reduced perceptual processing of other stimuli. Not only is there not

enough processing power to process all different potential stimuli in the environment, the attentional system also *inhibits* the processing of interfering stimuli. Both the limits of attention as well as the role of attentional inhibition will be explored in the course of this chapter.

There are several forms of attention, such as auditory or proprioceptive attention, which may be controlled by distinct brain mechanisms, and covering them all is beyond the scope of this review, which will be focusing on visual attention. However, just as there are many forms of attention, visual attention itself can also be subdivided into different types. For instance, visual attention can be location-, colour-, or even motion-based (Liu, Stevens, & Carrasco, 2007; Posner et al., 1980; Störmer & Alvarez, 2014), and though they are all undoubtedly important, the work in this thesis will focus on the first of these, which could also be dubbed *visuospatial attention* (VSA). It has been argued that location-based attention may be a special case attention (e.g. Liu et al., 2007; Posner et al., 1980). For instance, Liu et al. (2007) found that albeit both motion- and location-based attention were eventually equally effective, the latter was deployed faster. They attribute the faster time course of VSA to the early visual areas being retinotopically organised, and as such location can be used to direct attention more easily in early visual areas (Itti & Koch, 2001), while different types of feature-based attention are processed in later cortical areas. The main research questions presented in this thesis will address how VSA is linked with the execution of actions. As actions, at least in terms of the movement of body parts, involves movement in space, understanding how attention, 'moves' in space is also of critical importance. For this reason, before addressing how attention and movements are linked, I will be providing a brief overview of the general role of attention, followed by an overview of different features of VSA.

1.2 Limitations in our visual processing and Attention

We constantly receive a vast amount of visual information, but due to processing limitations we are not capable of attending the whole visual field simultaneously, or at least certainly not

at the same level of detail. That we do not pay equal attention to all the visual information we process should not be too surprising when one realises that not all of this raw sensory input has the same resolution. Leonardo da Vinci is reputed to have been the first person to make the distinction between foveal and peripheral vision, and visual acuity falls sharply outside the fovea (Jones & Higgins, 1947). The eye makes the most of this high-resolution foveal vision by performing 2-3 rapid eye movements a second, also known as *saccades*. The way in which attention is linked with the guidance of saccades will be reviewed in more detail in Chapter 2. However, though these quick saccadic sequences do a good job of quickly scanning the environment, we still are less aware of our surroundings than we may think. For instance, it has been known for a long time that visual information during eye movements is suppressed (for an early review see Matin, 1974). For instance Bridgeman, Hendry, and Stark (1975) found that participants failed to detect changes in position of stimuli in the course of a saccade. Not only that, but the bigger the saccade was the larger the change had to be in order to be detected. The reason why the visual input is suppressed may be in order to provide a spatially stable representation of the world. It is for this reason that, try as one might, one cannot observe one's own eye movements in a mirror.

A more striking example, now shown to psychology undergraduates in institutions around the world, was carried out by Simon and Chabris (1999). In their experiment, participants were asked to count either the number of passes one of two basketball teams made in a video. In one of the conditions, a person in a gorilla-costume would walk onto the centre, thump its chest, and then walk away. Despite this fairly untypical occurrence, a high proportion of participants failed to notice this event. If the counting task was rendered harder, with participants having to keep separate counts for aerial and bounce passes, then the proportion of participants who failed to spot the 'gorilla' was even higher. That a harder task makes the noticing of another event taking place more difficult further highlights that attention is a finite resource and is necessary for bringing facets of our surroundings to our awareness.

Do we attend to everything? The short answer is no, but this brings forth a wide range of questions, including how do we allocate attention, and how do we deal with distractors, among many others. We will now turn our own attention to a paradigm which has been particularly fruitful in trying to answer these questions: *the Posner cueing task*.

1.3 Studying VSA: Insights from the Posner Cueing Task

The traditional Posner cueing task, or just Posner task for short, essentially involves observing how the speed of stimulus detection or discrimination changes when its likely location is cued in advance, compared to performance at a uncued location. The general finding from a Posner task is that responses are faster when the stimulus matches the cued location, suggesting that the cue has successfully oriented attention to the designated location leading to faster stimulus detection/discrimination. We will now cover a seminal study by Posner and colleagues (1980) which deserves to be looked in a bit more detail, as it encapsulates the series of questions this versatile paradigm can attempt to answer.

1.3.1 A Demonstration of Paradigm Flexibility: Posner et al. (1980)

In each experiment participants had to respond when they detected the appearance of an LED, and compared the reaction times (RTs) when the location was correctly cued compared to when it was not.

In their first experiment, participants had to press a key at presentation of a stimulus on either side from central fixation, at either 8° or 24°. At central fixation, either a '+' was presented, or a number from 1 to 4, where the number indicated the likely target location from the far left to far right.

The main objective of the first experiment was to test whether there was a difference in target detection rates between 'mixed blocks,' in which the cued location could change from trial to trial, and 'pure blocks', in which the cued location was fixed for the duration of a block. In most blocks the target appeared at the cued location 79% of the time, and so there was a high

cue-validity. However, control condition for both kinds of blocks were also conducted, in which no location was cued (the '+' was never replaced) and the target was equally likely to appear in any of the four possible locations. Posner and colleagues found that for both types of blocks, people were slower than in the control condition when the LED appeared at an uncued location. More importantly, they found faster RTs at the cued location only in the mixed blocks. Why exactly this was the case is open to debate, but it is apparent that participants did not re-allocate attention on each trial when the location remains constant. Additionally, the fact that performance at the unexpected locations was worse in both conditions, may have some interesting implications on sustained inhibition of locations not deemed pertinent, but attentional inhibition is a topic we will get into in greater detail later in sections 1.5 and 1.8 of this chapter.

The second experiment investigated whether advance knowledge of the identity of the target would be as effective a cue as location. This time participants were presented one of 10 randomly selected capital letters at 7° on either side of fixation, and again had to press a button when it was detected. Participants were cued both the location (via an arrow) and the likely letter (presented below the location cue), both at 80% validity. Posner et al. found that only the location cue was effective in speeding up the responses, supporting the view of attention being to a good extent location based, at least in the visual realm, as supported by Liu et al. (2007).

So far these experiments involved only detection of a stimulus. It is possible that the cue did not actually enhance processing of information at that location, and all that it was doing was predisposing the participant to make a response based on more lax criterion on the information sampled at that location. In other words, participants may have been responding more 'recklessly' on less information, rather than actually processing the details at the cued location in more detail. To account for this, in Experiments 3 and 4 Posner et al. conducted a discrimination task rather than a detection one, where participants had to flick a switch

downwards if a small light appeared below a line, or flick it upwards if it appeared above it. Though the size of the Posner effect was smaller than in the previous experiments, suggesting that discrimination is indeed more challenging than detection, it was still present, and there were no differences in error rates. However it is important to bear in mind that the difficulty of the task may influence the detectability of attentional facilitation. It is possible that too challenging a task may be too insensitive and not detect attentional enhancement though it is present. There are limits as to how much attention can improve the processing of a visual stimulus, and for instance its physical properties may be below physical detectability. A good example of this will be seen in the empirical chapters of the present thesis, where we see that when a stimulus is shown for too brief a period of time, participants will perform at chance levels until the stimulus presentation time is increased (see the pre-test sessions in Chapter 8, p. 171). However if the task it too easy, as may have been the case for selecting the manual target in Experiment 4, then maybe no attention is allocated to said location as it is not needed. As will become apparent in the course of this thesis, both of these scenarios, where the task is either too difficult or too easy, should not be a small consideration in one's paradigms.

The final experiment consisted in testing whether attention can be allocated at will, by providing participants information in advance for the two most likely locations a probe was going to appear. As one would expect, the participants performed best at the most likely location, which was again cued by a central number like in the first experiment. The results are somewhat more interesting with regards to the second most likely location. Performance at the second most likely location was not significantly different from the most likely location if it was adjacent to the most likely location. However if the second most likely location was not adjacent to the most likely one, then performance decreased to levels seen at any other location, suggesting perhaps a strategic 'spread of attention' around the likely location in the former case, and no evidence for splitting attention in the latter. When two other experiments were run where the locations beyond the cued one were all equally likely, this adjacency effect

did in fact disappear, suggesting that attention was spread over a wider area when there was a strategic justification to do so. Both the issues regarding the shape and size of VSA, as well as whether attention can be split shall however be discussed in greater detail in section 1.6.3 (p. 25).

What is striking about this set of studies by Posner et al. (1980) is the large set of questions that this one set of studies attempted to address using modifications of the same paradigm. Many if not all of these questions are still under debate, but it is important to highlight them nonetheless. It addressed issues with regards to the difference between detection and discrimination of a stimulus, how attention appears to be more location- than object-based, whether attention can be allocated at will, and whether it can be split into two non-contiguous locations in parallel. All of this based on RTs and discrimination accuracies from a relatively simple cueing-paradigm. We will now look in more detail at how attention is oriented.

1.4 Orienting Attention: Exogenous and Endogenous Mechanisms

A common distinction which is made regarding the ways attention can be oriented is whether it is directed *exogenously* or *endogenously* (e.g. Hein, Rolke, & Ulrich, 2006; Nakayama & Mackeben, 1989; but see Awh, Belopolsky, & Theeuwes, 2012). The former is stimulus-driven, bottom-up and automatic (or at least semi-automatic, see Santangelo & Spence, 2008), and serves the purpose of allowing one to quickly adapt to changes in our environment. In contrast, endogenous attention is driven by top-down processes and by one's own internal goals. In the laboratory, the two are often studied using Posner tasks, but using different ways of cueing a location (Figure 1.1, p. 16). In the case of an endogenous cue, the upcoming location is cued by a central cue, possibly an arrow or other symbolic cue, as seen in the work by Posner et al. (1980) (but see Ristic and Kingstone, 2006). In a Posner task investigating exogenous cueing, the location may be cued not by a central cue, but by the onset of an event on the visual periphery, for example an increase in luminance of stimulus in the periphery, or the sudden appearance of a potential target there (e.g. Yantis & Jonides, 1990). This sudden

onset would usually result in the allocation of attention to the said location, though as we will see Yantis and Jonides show, there are a few exceptions. It is worth noting here that when people orient their attention, this tends to be accompanied by eye and/or head movements, but studies focusing on endogenous or exogenous attention tend to require participants to maintain fixation at the centre of the screen. This is known as *covert attention*, as opposed to *overt attention* which involves eye movements. The reason for this is to ensure that any perceptual enhancement at a location is due to shifts of attention, rather than resulting from foveating the target. Recent work also suggests that exogenous attention is tied to eye movements, while endogenous attention is not (Smith, Schenk, & Rorden, 2012).

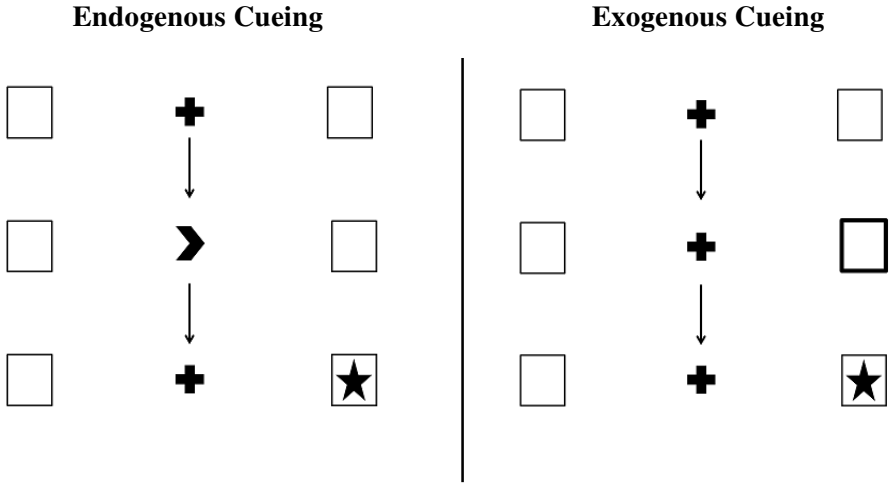

Figure 1.1. Examples of a Posner task utilising either an endogenous (left) or exogenous cue (right). In this fictitious example participants would have to respond at the appearance of the target star-stimulus. In the endogenous case the central arrow is validly cueing the location of the target, while in the exogenous case this location is cued by a preceding increase in luminance. In invalidly cued cases the star would have appeared inside the left box.

As exogenous attention is driven by changes in the environment which might require one to adapt to them quickly, it should come as no surprise that exogenous attention is deployed more quickly than its internally driven counterpart. Endogenous attention, which also has the property of being able to be sustained for longer periods of time, takes around 300ms to be deployed, compared to the peak experienced at 100-150ms by the more transient exogenous attention (Chica & Lupiáñez, 2009; Liu et al., 2007; Nakayama & Mackeben, 1989; Remington, Johnston, & Yantis, 1992; Remington & Pierce, 1984; Woodman & Luck, 2003). In these experiments the time course of attention is typically measured by observing how

perceptual performance is affected by altering the time between the cue onset and an intended target. The logic behind this is that as one gradually increases the time interval between the onset of a cue and the cued target, one will first start to see an increase in perceptual performance (possibly assessed by better target discrimination) as more attentional resources are allocated at the cued location. Perceptual performance will eventually peak, which will give one an indication of how long it took to allocate the maximum amount of available attentional resources, before subsiding again as attention is allocated elsewhere. It is worth noting that the time course of endogenous attention includes also the amount of time it takes for the participant to interpret the orienting cue, assuming there is one. In the example shown in Figure 1.1, this would be the time to interpret the central arrow cue.

The presence of two different orienting mechanisms brings forth the question on how they interact with one another, as they are essentially competing for the 'attention' of a limited resource. While we are engaging endogenous attention for specific task, another relevant stimulus might appear somewhere else in our visual environment. The new stimulus might be important, possibly a source of danger to oneself, and as such it would be critical to attend to it. However, if one was not able to maintain the focus of attention on a single item for extended periods of time then it would be impossible for one to finish dealing with whatever the intended target of our attention was. This attentional-balancing act is resolved by the interplay between endogenous and exogenous attention. For instance, when the endogenous cue is reliable, the attentional capture by an exogenous cue can be suppressed (Theeuwes, 1991; Yantis & Jonides, 1990). Yantis and Jonides (1990) demonstrated this by varying the validity of a central cue, and having a sudden onset stimulus, which could in some cases be the target or a distractor. On the trials in which the the exogenous stimulus was not the target, the latter replaced a stimulus which was already on screen. When the central cue was 100% predictive, if the exogenous stimulus was not at the cued location, this had no effect on the participants response times, meaning that the exogenous stimulus did not succeed in capturing attention.

However, as the validity of the central cue decreased, the more the exogenous cue captured attention. Not only that, but the longer in advance the cued location was known before the onset of a stimulus, the smaller the effect of the exogenous cue, supporting the slower time course of endogenous attention. Similar results regarding cue validity have also been obtained by Theeuwes and Burger (1998), who also found that even a highly salient distractor can be suppressed, when its visual properties are known in advance. A demanding task requiring endogenous attention has also been demonstrated to suppress not only visual exogenous cues, but auditory ones as well (Santangelo, Olivetti Belardinelli, & Spence, 2007). This may be due to the exhaustion of attentional resources available (Lavie, 1995), or even inhibition of one orienting mechanism by another. We will now proceed to look into the role of inhibition in attention.

1.5 Attention and Inhibition

As addressed in section 1.2, we receive a vast amount of visual sensory information, and we have just discussed in section 1.4 both endogenous and exogenous mechanisms for orienting attention to a select part of it. The question arises how information is processed at locations outside the focus of VSA. In this next section we will see that some of this information is not merely unattended, but actually inhibited. Furthermore, inhibition also minimises the amount of interference from distractors, in particular the visual information around the focus of attention, and can also result in more efficient visual search strategies. We will revisit the concept of attentional inhibition again in section 1.8 (p. 31) and in the next chapter with relation to eye and hand movements (sections 2.4.3 and 2.5.2 respectively).

The difference between inhibition and merely not allocating attention is neatly encapsulated in a study conducted by Wühr and Frings (2008). In a classic Stroop task (Stroop, 1935) participants have to report the colour in which different words are presented. The difficulty arises in the fact that colour-words themselves are used, which may or may not be congruent with the colour in which they are presented. When the colour and word are incongruent with

one another, participants' RTs are slower and they make more mistakes than when they are congruent, and this is known as the Stroop effect. The Stroop effect demonstrates how reading is a highly automatic process which is difficult to inhibit. In Wühr and Frings' experiment, participants were presented with two overlapping objects (a square and a circle) of different colours. Participants had to report the colour of one of these two objects, while congruent or incongruent colour-words appeared either within the target-object, the non-target object or in the background. The incongruent words presented within the target object induced the highest Stroop effects, demonstrating higher competition between competing information (i.e. the colour and the word) due to attentional enhancement of the target object. More crucially, the Stroop effect was weakest for trials in which the colour-words appeared within the non-target object, even compared to when the words appeared in the background. This demonstrates general inhibition of the overlapping, non-target object resulting in a weaker Stroop effect, compared to the amount of interference induced by the background, and thus elegantly illustrates the difference between simply not attending a location and inhibiting one.

In the above study it is a whole object which appears to be inhibited, but inhibition plays already a role in normal allocation of VSA. Several recent studies have shown that the focus of attention is surrounded by an annulus of inhibition. This results in what is known as the Mexican Hat model of attention (Cutzu & Tsotsos, 2003; Hopf et al., 2006; Hopf, Boehler, Schoenfeld, Heinze, & Tsotsos, 2010; N. Müller & Kleinschmidt, 2004; N. Müller, Mollenhauer, Rösler, & Kleinschmidt, 2005), where this inhibition allows the focus of attention to be processed with less interference from adjacent stimuli (Figure 1.2, p.20). Interestingly, inhibition of adjacent locations may not be restricted to the domain of VSA, but be a more generic way in which attention operates (Treue, 2014). The equivalent of a Mexican Hat distribution of attention has recently been found outside the realm of VSA but in the realm of colour: when a particular colour is cued (e.g. red), processing of stimuli of the said colour is increased, while the processing of stimuli of a similar colour (e.g. orange) is inhibited

compared to more dissimilar colours (e.g. yellow) (Störmer & Alvarez, 2014). Inhibition therefore seems to play an important role in managing to focus one's attention to a target, not only in the domain VSA, but in feature-based attention if not beyond. Furthermore, an 'inverted Mexican Hat' distribution of inhibition has also been observed (Finke, Ostendorf, Martus, Braun, & Ploner, 2008). Subjects had to perform a memory-guided saccade, while also discriminating a stimulus which appeared either at the location to be saccaded to or on either side of it. This resulted in a focus of inhibition at the location to be saccaded to, as measured by slower discrimination of the stimulus, surrounded by an annulus of facilitation. This further enhances the view that this distribution of attention is a more inherent property of the attentional system.

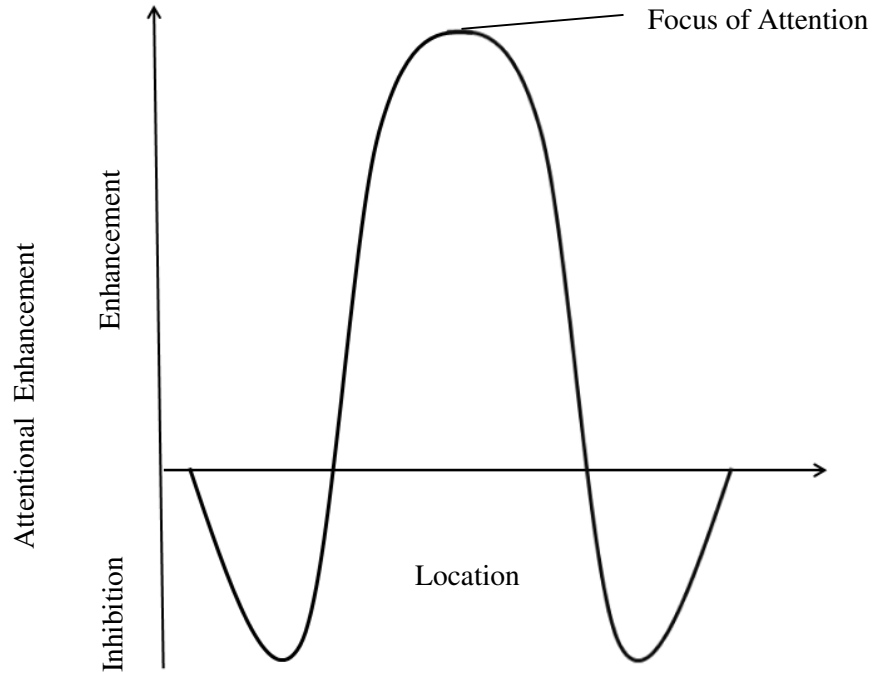

Figure 1.2. ***The Mexican Hat Model of Attention*****: The focus of attentional enhancement is surrounded by an annulus of attentional inhibition.**

We will revisit attentional inhibition again when looking at the neural mechanisms of attention in section 1.8 (p. 31), and when discussing the links between perception, attention and action

in section 2.4.3 (p. 48), but here I hope to have illustrated the role of inhibition in VSA. This primarily involves the inhibition of distractors (Wühr & Frings, 2008) and the area around the focus of attention. We will now proceed to discuss in more detail the way in which VSA 'moves' and is distributed across the visual landscape.

1.6 Under the Spotlight: The Movement and Shape of Attention

As we do not attend to everything in our visual environment, a question which arises is how does attention 'sweep' the visual landscape? Focused VSA has often been compared to a spotlight which scans the environment, resulting in enhanced processing wherever it is focused on (Posner, 1980). As pointed out by Yantis (1988), this is a useful metaphor to describe some aspects of how VSA is allocated, rather than an actual theory. For instance, the spotlight does not capture the role of inhibition in attention, which we have just seen is crucial. We will take a closer look at the spotlight metaphor and some of the issues associated as a way to guide our understanding of how VSA moves and adapts, but for detailed reviews see Cave and Bichot (1999) and Carrasco (2011).

1.6.1 Moving the Spotlight

We have covered two of the main mechanisms for orienting attention, but this does not address how attention 'moves' to the oriented location. Does it, like a spotlight, sweep across the environment in a smooth and analogue way? The brief answer is that it does not. In a fashion similar to eye movements attention appears to 'jump' from one location to the next rather than sweeping between them. Contrary to eye movements, the speed at which attention is allocated to a location in space does not change with distance.

What is the evidence for a 'jumping spotlight'? Several experiments fail to find slowing down effects of placing distractors between a target and fixation (Murphy & Eriksen, 1987; Sperling & Weichselgartner, 1995). If the spotlight were to be sweeping between the two locations, then a distractor placed on the way should capture it, resulting in a slowing down effect. Work

by Chastain (1992a, 1992b) also seems supports this conclusion. In one of his experiments (Chastain, 1992a), a distracting probe could appear either between fixation and a target, or in a diametrically opposite location from the target, and no difference in the amount of interference was found for either one. In the second study (Chastain, 1992b), following a blank screen, participants were first cued to one possible location for a target to appear, and if the probe did not appear there, then a second location would be cued, using a range of interstimulus intervals (ISIs). It was hypothesised that if attention moved like a spotlight, then there would be a period during which the spotlight would be moving between the two locations. If the discrimination target appeared during this time, then discrimination performance at either location would drop. However, if attention was shifted discretely from one location to the other, then as less attention would be allocated to the first location and more attention to the second, and on average the performance collapsed across the two locations should remain constant. This is indeed what Chastain found. That being said, these findings should be taken with a pinch of salt. There were only 4 possible locations, and the second location was always the one opposite to the previous location. This renders the task more predictable, and as such could have led to faster shifts of attention which would make it hard to distinguish between a 'sweeping' and a 'jumping spotlight' (Hahn, Ross, & Stein, 2006).

However, the fact that the eccentricity of the stimuli in one's visual field does not appear to influence the speed with which attention shifts from one location to the next may provide a more convincing point against a sweeping spotlight. For instance, Remington and Pierce (1984) found no differences in RTs in a Posner task when the target was either at 2 or 10 degrees from central fixation. Similar findings were obtained by Kröse and Julesz (1989), as well as with multiple cued targets (Eriksen & Webb, 1989) and in same-different matching tasks, where two stimuli had to be judged as either being the same or different (Kwak, Dagenbach, & Egeth, 1991; Sagi & Julesz, 1985). Sperling and Weichselgartner (1995) too

failed to find an effect of manipulating the distance between peripherally and foveally attended visual streams.

Whichever is the mechanism with which attention is allocated around a visual scene, an important related question is how fast this is achieved. As we have covered before, this may depend on whether attention is oriented exogenously or endogenously (section 1.4), which conform with the point made by Awh and Pashler (2000), who found that the literature tends to report times ranging from 100ms to 400ms. Another factor that may play a role are individual differences. These however have been much less studied in the field, possibly also due to the large number of participants required for a meaningful study of them. However, it is worth noting that white matter changes have been implicated with decreased speed of attention (Ylikoski et al., 1993), so individual differences in biological makeup, at least with regards to white matter, are likely to be a source of individual variability. Nurture may also play a role, with extensive practice having been shown in one case to increase speeds of attentional shifts down to even 30ms per item (Czerwinski, Lightfoot, & Shiffrin, 1992). Individual differences in attention shall be discussed in more length in sections 6.1.7.3 (p. 207) and 7.3. (p. 222)

1.6.2 The Shape of Attention – It is good to be flexible

Our surrounding environment consists of several potential sources of interaction, comprising a wide range of shapes and sizes. With this in mind, it is difficult to conceive of an attentional spotlight with immutable shape and size that would be up to the task of scanning one's environment. Contrary to some items of clothing, one size does not fit all, and this can be seen in the way in which the shape and size of the spotlight adapts to the task at hand. Eriksen and St. James (1986) have proposed a zoom lens model of attention, where the size of the attentional spotlight varies. This proposal was followed up by Castiello and Umiltà (1990), who carried out a Posner-like cueing task, where a stimulus would appear within the boundaries of a previously presented box. They found that the larger the size of the box, the

slower the RTs, thus suggesting that a bigger spotlight somehow diffuses or dilutes attentional processing. There is work suggesting that the task difficulty does indeed influence the size of the spotlight (Ahissar & Hochstein, 2000). Ahissar and Hochstein (2000) trained participants to detect a target which could appear in an array of similar stimuli, and varied the possible positions in which it could appear, as well as the stimulus onset asynchrony (SOA) between the stimulus and the following masking elements, thus altering the amount of time available to process the target. Following this training, they observed how participants performed at detecting the target when it could appear anywhere on the array. They found that when participants had previously been trained to detect the target appearing at one of two locations on the horizontal meridian, detection of the area in between (encompassing central fixation) was improved, which would correspond to an increase in the size of the focus of attention. Similar effects were found with participants trained with the target appearing at one of two locations on a *diagonal* meridian, but to a lesser extent, which the authors attribute to performance overall being worse in such a condition, and perceiving along a diagonal meridian thus being harder. Furthermore, they found that at shorter SOAs, perceptual performance was more localised to the trained locations. This suggests the possibility that attentional allocation is more focused at short intervals, with the spread increasing with time. An effect of task difficulty was also observed between participants, as participants who were better at the detection task at the start (i.e. performed better at lower SOAs), also had a wider spread of their attentional window. This is again consistent with the task difficulty determining the size of attentional spread, with participants who find the task easier having a wider spread of attention.

If the size of the spotlight is flexible, what about its shape? One of the most striking examples of the flexibility of this shape was carried out by Juola, Bouwhuis, Cooper, and Warner (1991). Participants were presented with three concentric rings along which a target stimulus could appear, and the ring along which the target would appear was cued in advance. Regardless of

which ring was cued, participants performed better when the target appeared at the cued ring, suggesting an annular distribution of attention, which accounted for more variance of the data than serial shifts. Similar results have also been obtained more recently by Kerzel, Born and Schonhammer (2012), who found that distractors in a smaller ring did not interfere with the stimuli presented on a larger ring around it, when the latter was cued. Inhibition of an area within another, or a 'doughnut of attention' may at first appear to contradict the view of a Mexican Hat Model, where attention is focused primarily at the centre rather than the edges. However, this matches well with the previously mentioned, 'inverted Mexican Hats', i.e. a focus of inhibition with a facilitatory annulus around it (Finke et al., 2008). This 'attentional dougnut' can thus be accounted for by an inverted Mexican Hat. However, it is important to note that there have been failures to reproduce annular distributions of attention (Eimer, 1999, 2000; Heinze et al., 1994; Posner et al., 1980), and so even though VSA appears to be flexible enough to take on a ring-like shape, this formation may arise only under specific circumstances, and not be an easy one to produce (Beck & Lavie, 2005).

1.6.3 Flexible enough to do the split?

We have so far seen that the way in which VSA is allocated is flexible, but does this include being able to split across multiple locations? In order to convincingly show that attention has been allocated in parallel to two non-contiguous locations, one has to show that the area between the two locations does not receive attentional facilitation, and also that an attentional spotlight would not have the time to be allocated to both locations in a serial fashion. This is where the difficulty lies: VSA can adapt its shape (Juola et al., 1991; Kerzel et al., 2012), and can be oriented fast with a speed which appears to improve with practice (Ahissar & Hochstein, 2000; Czerwinski et al., 1992). A recent review by Jans, Peters, and Weerd (2010) went as far as to say that to date there were no experiments claiming to show the splitting of attention which could rule out either a fast serial movement of the spotlight or re-arrangement

of the spotlight's shape, either because they were too easy or because they did not probe the visual landscape in enough detail.

Long probe presentation times cannot rule out serial shifts of attention, and not probing intermediary locations does not control for an increased size or a change in shape of the attentional spotlight. Though the first of these two points is fairly uncontroversial, the second one is not. Failures in finding annular distributions of attention suggests that there may be a limit to how flexible the shape of VSA, and an annular arrangement may only arise under specific circumstances (Lavie & Beck, 2005). This point is echoed by Cave, Bush, and Taylor (2010), who state that Jans and colleagues' criteria may be too stringent and impossible to satisfy in practice, and that Jans et al. rule out a split attention account on occasions when this would be the most parsimonious explanation. An infinitely malleable spotlight, easily curving around distractors, seems less plausible than attention being allocated to two separate locations in parallel, possibly divided by areas of attentional inhibition (Awh & Pashler, 2000).

Cave and colleagues re-assess the studies covered by Jans et al. by using their own re-defined criteria, and though they find that most of the studies indeed are not stringent enough to meet the criteria, a few do (Awh & Pashler, 2000; Bichot, Cave, & Pashler, 1999; Kawahara & Yamada, 2006). Crucially, these had sufficiently short presentation times, controlled for fixation, and ensured that more attention was allocated to the target location than to the non-target location. For instance, Awh and Pashler (2000) carried out a series of experiments presenting two targets within an array of distractors, and found facilitation at pre-cued locations. More crucially, they failed to find facilitation at uncued locations, including when targets appeared between the cued positions. Interestingly, they found that cueing effects vanished in the latter experiments with the removal of distractors, suggesting that the split of attentional foci might be induced by the inhibition of distractors. Alternatively the removal of distractors may lead participants to adopt a different attentional orienting strategy, and just increase the size of the attentional focus, as suggested by the zoom lens model.

Cave et al. (2010) agree that serial shifts of attention could explain many of the findings. In a manner reminiscent to failures of some experiments in finding rings of attention, it is only in particular tasks that attention may result in being split. For instance, as we saw in the study by Awh and Pashler (2000), split foci of attention may be generated by the inhibition of distractors located between the targets. More recently, Awh and Pashler's paradigm has been used by Feng and Spence (2013), who investigated the role played in the spatial arrangement of the cued targets in whether attention is split or not. By alternating the distance between two cued targets and probing discrimination performance also between these locations, they found that split attention occurred when the distance between the cued locations was larger. In contrast at shorter distances a unitary focus of attention was observed. Thus, the spatial distribution of stimuli is of critical importance in determining whether VSA has a unitary of split focus of attention.

Whether VSA is unitary or split is influenced also by a participant's internal goals and expectations (Jefferies, Enns, & Di Lollo, 2013). Jefferies and colleagues presented participants with 2 streams of numeric stimuli, and the first task was to identify two letters that would appear either within these streams, or between these two streams and fixation. Following the simultaneous presentation of the two target letters, another two were presented either within the two streams or between them, and subjects had to also report their nature. Jefferies et al. altered the likelihood with which the two targets would appear within the first two visual streams or between them, and found that when subjects knew in advance that the targets were going to appear at the stimuli streams on the edges, two separate "peaks" of attentional allocation would occur. This led to poor discrimination of the second set of targets, presented in between the two locations. However, in conditions where the first targets could appear both within the streams and between them, this resulted in a unitary focus of attention, encompassing all four locations.

Both the results by Jefferies et al. (2013) and Feng and Spence (2013) have been replicated by Botta and Lupiáñez (2014), who found both the effects of target predictability inter-target distance for inducing a split of attention. However they go a step further and state that they only found this effect with exogenous but not endogenous cueing of attention. In the examples we have covered the target locations were exogenously cued before the appearance of the targets, and Botta and Lupiáñez found that endogenously cueing locations did not induce splitting of attention, and merely produced a single focus of attention. One must be careful though to over-interpret from these results, as they may be contingent on the effectiveness of the endogenous cues used. In this study the stimuli were arranged in a circle around fixation, and each location corresponded to the number on a clock that would be in said position. However, there were only 8 stimuli, so it may be that this arrangement did not correspond to a typical clock-face closely enough for the cues to be easily interpretable. However, athough said study may not be sufficient to fully rule out the possibility of endogenously-induced splits of attention, it certainly shows that this may be harder to induce, even when the endogenous cues were presented for longer (300ms) than the exogenous cues (100ms).

A final point worth mentioning is that there is some evidence that the splitting of attention may be difficult to sustain for longer periods of time. Dubois, Hamker, and VanRullen (2009) showed participants two targets of a specific colour, among distractors of a different colour, and first asked to judge whether the shapes of the two targets matched each other or not. Following this, letters were briefly shown at the locations of the targets and distractors, and subjects were told to report as many of the letters as they could. The ISI between the initial targets and the letters was varied between trials, and the results indicated that based on the letter-detection task, the split of attention induced from the first task was sustained in the second task only for the shorter ISIs (100-150ms). At longer intervals the focus of attention was unitary, thus suggesting that the split of attention is more difficult to maintain.

The evidence does seem to suggest that under the right circumstances, the attentional spotlight can be split to multiple non-contiguous locations, and thus allocation of attention is again more flexible than a spotlight metaphor might initially suggest. The spatial distribution of the targets, the presence (and inhibition) of distractors, participants' goals, how attention was cued and even the time course between stimuli all play a role. That attention is divided only under certain circumstances not only helps explain cases in which no splitting of attention was found (e.g. Woodman & Luck, 2003), but it also makes sense in the context of attention being a finite resource. If there was no cost in splitting attention, then there would be no reason for attention to not be divided indefinitely. Also, if attention was easily diverted and was diffused between multiple stimuli rather than to one's primary target or focus, then the processing of said target and subsequent interactions with it would be impaired (S. F. Feng, Schwemmer, Gershman, & Cohen, 2014). Nevertheless, there are circumstances when attending to multiple locations may be useful and necessary, such as when planning sequences of saccades (Baldauf & Deubel, 2008a; Gersch, Kowler, & Dosher, 2004; Godijn & Theeuwes, 2003) or hand movements executed in quick succession (Baldauf, Wolf, & Deubel, 2006; Baldauf, 2011). The relationship between attention and action is an important one, and it shall be the central topic of discussion in the next chapter. We will be also re-visiting the question regarding the splitting of attention in more detail from Experiment 5 (p. 136).

1.7 Object-based Attention – A quick look

In the previous section we have seen how VSA moves in space, in a manner which is flexible and versatile, adapting to the circumstances and environment. However a key determinant of the shape that attention can have and where it is allocated is the target of its focus (or foci). We do not tend to pay attention to a blank area of space, but to different objects around us. VSA therefore needs to adapt to the wide range of objects that surround us, which in turn influence the way in which attention is allocated. A now classic study on object-based attention was carried out by Egly, Driver, and Rafal (1994), who found participants responded faster

when a stimulus appeared within a cued object than at an equidistant location outside of it (see Figure 1.3, p. 31, for an illustration of the trial sequence). The fact that more attention is allocated to areas within the same object than to other equidistant locations suggests that the locations within an object are prioritised over others, and some findings suggest that distinct mechanisms underlie object- and location-based attention (e.g. Chou, Yeh, & Chen, 2014). Distinct as these mechanisms may be, they also seem to interact with one another. A study by Soto and Blanco (2004) cued both a possible location and/or the moving object in which a stimulus could appear and broadly replicated Egly et al.'s findings, finding both object- and –location-based attention. However, the location-based effects were stronger, and object-based attention only emerged when the location was invalidly cued, suggesting that the cued location takes precedence over the object.

A further point was made by Hollingworth et al. (2012), who suggest object-based attention and location-based attention appear to be linked to each other, with the former possibly also arising through spatial mechanisms. For instance, within object-based attention there is a gradient of attentional allocation, with less facilitation occurring the further away from the cue within the object the discrimination target appears (Egly et al., 1994; Hollingworth, Maxcey-Richard, & Vecera, 2012). This is consistent with the presence of a spatial component within object-based attention itself. (Interestingly, the objects used by Hollingworth and colleagues included rings and half-rings, thus offering further support to the annular distribution of attention mentioned in p. 24.) For a recent and extensive review on object-based attention, see Reppa, Schmidt and Leek (2012). This may lend some support to the view of VSA might be the default-modality of selective attention, over other features (Liu et al., 2007).

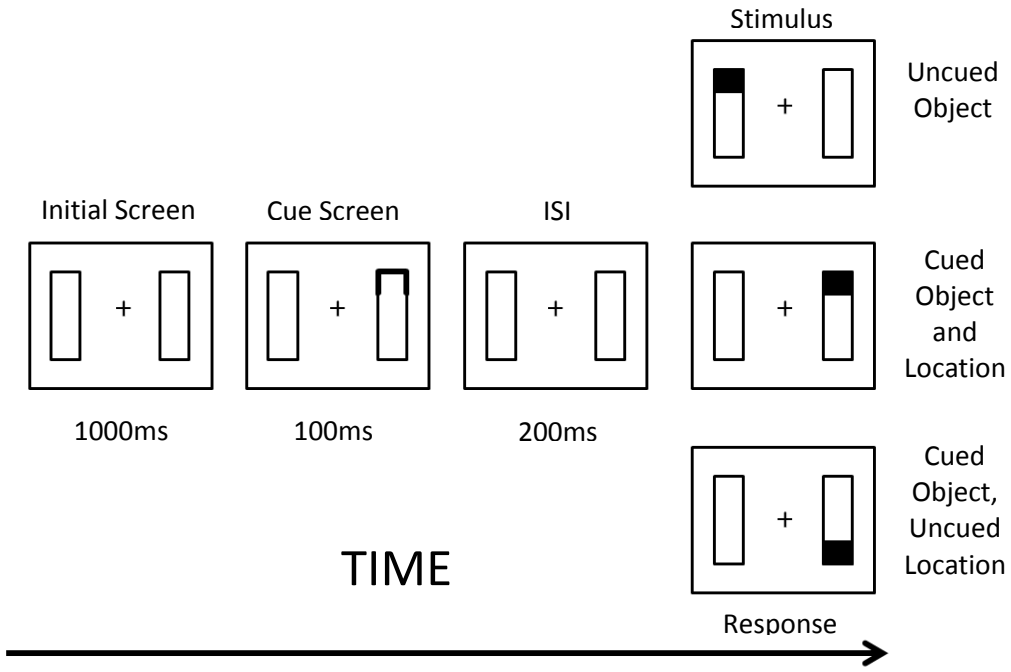

Figure 1.3. Illustration of a typical trial sequence in Egly et al. (1994), not drawn to scale. Participants maintained fixation at the centre, and after a brief interval an increase in luminance of one of the ends of the object cued the location of an upcoming target. The stimulus presentation was preceded by a brief interstimulus interval (ISI), after which it appeared either at the uncued object (top right), at the cued object and location (mid-right), or at the cued object and location (bottom right). Subjects responded faster to stimuli presented at the uncued location in the cued object than at an equidistant stimulus in the uncued object. A version of the task with the objects arranged horizontally was also conducted, which produced the same pattern of results.

1.8 How attention leads to perceptual enhancement – Some neural underpinnings

We have mainly focused on where attention is allocated within the visual environment. Nevertheless, before we move on to the next chapter which explores the relationship between movement and attention, it is relevant to also consider how attention may result in enhanced perception. We will see that there are several mechanisms by which attention appears to act, which befits the flexibility VSA has displayed thus far. For recent reviews on the subject see Carrasco (2011) Anton-Erxleben and Carrasco (2013).

Attention has been shown to result in increased contrast sensitivity at the attended location, but also decreased contrast sensitivity at the location of distractors (Carrasco, Penpeci-Talgar, & Eckstein, 2000; Liu, Pestilli, & Carrasco, 2005; Pestilli & Carrasco, 2005). Similar results

have also been reported earlier for the detection and localisation of stimuli (Bashinski & Bacharach, 1980). These studies highlight how attention appears to both enhance the neural representation of the target, and to inhibit the representation of distractors, and the perceptual enhancement is a result of an interplay between the excitation and suppression of population of neurons in different visual areas (e.g. Herrmann, Montaser-Kouhsari, Carrasco, & Heeger, 2011).

The enhancement of the attended stimulus derives from attention increasing the response of neurons representing the target (e.g. Baschinsksi & Barrach, 1980; Dosher & Lu, 2000; Ling & Carrasco, 2006). This increase in response is characterised by either *contrast gain* or *response gain* (e.g. Huang & Dobkins, 2005). Contrast gain can be expressed as the neurons representing the attended area requiring less stimulation to fire, while response gain sees a constant multiplicative amplification of the neural response. In other words, in the former case the neurons start responding to weaker stimuli, whereas in the latter case a stimulus of the same strength as before is required to elicit a response, but when it does so, the size of the response is amplified. Reynolds and Heeger (2009) proposed that whether attention resulted in contrast or response gains depended on the relative sizes of the attentional field and the stimulus. According to their normalization model of attention, a small stimulus presented in a large attentional field would result in contrast gains, while a relatively large stimulus presented in a small attentional field would result in response gains. Recently Herrmann, Montasser-Kouhsari, Carrasco and Heeger (2011) found evidence in support of the normalization model of attention. They varied the size of the attentional field by varying the uncertainty of the upcoming target location and the target's size. Their results matched the predictions of Reynolds and Heeger's model (2009), while also confirming that higher levels of uncertainty of the upcoming target location yielded a wider focus of attention. The current research on attentional enhancement seems to indicate that the underlying mechanisms of perceptual

enhancement of an attended stimulus depends on the context, which fits with the flexibility of the attentional spotlight we have seen so far.

Another prominent effect of attention is that it can increase spatial resolution at the attended location. As with contrast sensitivity (e.g. Pestilli & Carrasco, 2005), this enhancement does not occur without a cost, and the spatial resolution outside of the attended location has been shown to decrease (Montagna, Pestilli, & Carrasco, 2009). One of the key underlying processes believed to underpin changes of spatial resolution is a change in size of the receptive fields of the different neurons. Attention has been shown to shrink the receptive fields of neurons, thus allowing for more fine-tuned neural activity which results in higher perceptual acuity (e.g. Moran & Desimone, 1985; Shalev & Tsal, 2002).This shrinkage occurs due to the increased weighting of input from neurons corresponding to the attended area, which inhibit the firing of neighbouring neurons. Behavioural evidence for attention enhancing spatial resolution includes attention benefits in acuity tasks being the greatest at larger eccentricities, where the baseline spatial resolutions is lower (Carrasco, Williams, & Yeshurun, 2002; Yeshurun & Carrasco, 1999), as well as from performance in texture segmentation tasks (e.g. Yeshurun & Carrasco, 1998; Yeshurun, Montagna, & Carrasco, 2008).

Just as attentional enhancement has been linked with increased neural activity, attentional inhibition has been linked with decreases (e.g. Seidl, Peelen, & Kastner, 2012; Slotnick, Schwarzbach, & Yantis, 2003). This inhibitory process has been shown to be flexible, in that the more intense or probable the distractor, the more inhibition is applied to it (Serences, Yantis, Culberson, & Awh, 2004; Tipper, Howard, & Houghton, 2000; Wyatt & Machado, 2013). Models by Itti and Koch (2000) and Tipper et al. (2000) suggest that enhanced neural activity for the attended location will also result in decreased activity in the area surrounding the attended location. This is consistent both with the proposed mechanisms by which the receptive fields of neurons shrink and lead to increased spatial resolution (e.g. Anton-Erxleben & Carrasco, 2013), but also with the Mexican Hat Model of attention (e.g. Cutzu & Tsotsos,

2003) (see Section 1.5). Dosher and Lu (2000) proposed two main ways in which inhibition is involved in attentional control (see also Lu & Dosher, 2008), which Carrasco has distinguished as mechanisms for noise exclusion and distractor suppression (2011). The first one is deemed more common (see Carrasco, 2011), and works by excluding the stimulation provided by external noise (e.g. distractors). The external noise is determined and excluded via the application of appropriate filters on stimuli that do not match the current perceptual template, which in turn is determined by a range of factors such as spatial location or known target properties. This mechanism comes into play in situations with higher levels of noise. The second mechanism is a general suppression of the activity of neurons coding for stimuli that do not match the current perceptual template, and is applied equally in circumstances with high and low level of noise (Dosher & Lu, 2000; Lu & Dosher, 2008). It is important to note that these two inhibitory mechanisms do not exclude one another, and in all likelihood work together with each other, as well as with mechanisms for attentional enhancement (Carrasco, 2011).

1.9 Conclusions on VSA – What is it and how does it work?

Attention, even when confined to the visual domain, is a vast and complicated field, but in the course of this chapter I hope to have touched upon some of the key functions of VSA, as well as how it works. In essence, the purpose of VSA is to ensure the efficient processing of key features in our surrounding visual environment. The need for such a mechanism comes from our inability to fully process everything simultaneously. Inhibition of non-target stimuli plays an important role in the management of this limited source (e.g. N. Müller et al., 2005; Wühr & Frings, 2008), which is oriented by internal goals (endogenous attention), or by bottom-up stimulus properties (exogenous attention). The perceptual enhancement induced by VSA has often been compared to a spotlight (Posner, 1980) or a zoom lens (Eriksen & St James, 1986), and though there is some applicability in these metaphors, they belie the elegant flexibility with which our limited attentional capacity is managed to counter its limitations. Contrary to

a spotlight, attentional shifts are distance-invariant (e.g. Remington & Pierce, 1984), and are discrete rather than analogue (e.g. Chastain, 1992b). Task difficulty and available attentional resources appear to play a big role in how VSA is allocated, not only does the size of the attentional focus change with the task (e.g. Ahissar & Hochstein, 2000), but so does its shape. Under the correct circumstances, VSA can adopt a more exotic shape (e.g. Hollingworth et al., 2012), and even split onto two non-contiguous locations (e.g. Jefferies et al., 2013).

We are constantly processing visual information from an ever-changing visual environment. Though our visual acuity is limited, we are in possession of a flexible and dynamic system managing our attentional allocation, which manages to fulfil its role well enough that we are not often aware of its limitations. However, we do not perceive the world around us just for the sake of perceiving, but in order to guide our interactions with the world. The next chapter will be exploring the link between our actions and attention in more detail.

Chapter 2: Attention, Perception and Action

2.1 Introduction

In the previous section we conducted a general overview of the way in which attention gets allocated into our visual environment. What we saw was a system that is flexible and dynamic, adapting to a wide range of stimuli and situations. In this chapter we will focus on how attention is tied to the way in which we interact with the environment, by providing brief overviews of two different theories which may explain the links between attention and action, namely the premotor theory (Rizzolatti, Riggio, Dascola, & Umiltà, 1987) and the visual attention model (VAM; Schneider, 1995). This will be followed by an overview of the effect attention has on saccades and manual movements, before concluding with a brief assessment of the two theories.

2.2 The Premotor theory of Attention

In 1987 Rizzolatti, Riggio, Dascola, and Umiltà conducted an experiment to investigate the orienting of attention across the vertical and horizontal meridians. Subjects had to respond to a stimulus which would appear in one of four locations, which, depending on the condition, were aligned horizontally above or below the fixation point, or vertically on either side. The location of the upcoming stimulus was cued endogenously by a digit appearing in the centre, which was either valid, invalid, or stated that all four locations were equiprobable. The design is relatively simple variation of an endogenous Posner task, and yet at the time of writing, this single-study paper has garnered 1193 citations according to Google Scholar, and has generated one of the most influential current theories of attention. Where was the novelty in Rizzolatti's findings?

In their experiment Rizzolatti and colleagues (1987) asked participants to respond manually as quickly as possible to the appearance of a stimulus. Participants were fixating on a square

at the centre of the screen, and the stimulus could appear at one of four possible location, which were demarked by four boxes which were arranged either horizontally above or below fixation, or vertically to the left or right of fixation. The likely stimulus-location was indicated by a number which appeared at the box at fixation, which matched one of the four cued boxes. Examples of the vertical and horizontal stimulus arrangement can be seen in Figure 2.1.

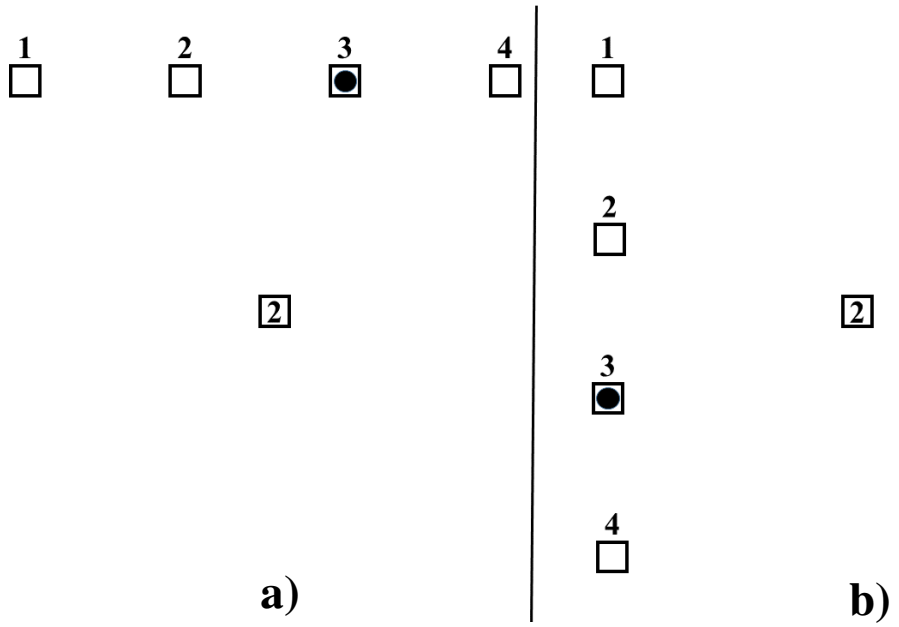

Figure 2.1. Examples of the vertical and horizontal stimulus displays used by Rizzolatti et al. (1987). In the above example the stimulus could have appeared within either a) a location vertically above fixation, or b) to the left of fixation. The possible target locations could also be below or to the right of fixation (not shown). In the above examples the most likely location for the stimulus to appear was the box numbered with '2', as indicated by the number at fixation, and yet the stimulus appeared at box '3'. Rizzolatti and colleagues found that in such a circumstance participants were slower to respond to the stimulus than if it had appeared at location 1. For explanation and discussion see text. Not drawn to scale.

Like other literature on endogenous attention covered in the previous section, they found that invalidly cued trials elicited slower reaction times than validly cued trials. More interestingly, however, they also found that RTs were slowed down even further when the invalidly cued stimulus was on the other side of both the vertical or horizontal meridian, and contrary to similar findings, the attentional facilitation did not blanket the whole cued hemisphere (Hughes & Zimba, 1985). They also found a smaller effect of distance between the cued and actual target location on invalidly cued trials. A similar effect of crossing the vertical meridian was reported by Downing and Pinker (1985), who attributed this effect to be caused by the

areas by the fovea to be represented in greater detail in the visual cortex, in a phenomenon known as *cortical magnification*. This would result in the attentional spotlight taking longer to traverse the representation of the fovea. However, as we have seen in section 1.6.1, there is good evidence that attentional spotlight does not sweep in an analogous way through the landscape (e.g. Chastain, 1992; Kwak, Dagenbach, & Egeth, 1991; Remington & Pierce, 1984), and the stimuli used by Rizzolatti et al. (1987) were several degrees away from the fovea. Their proposed explanation is what made this particular study as influential as it is.

Rizzolatti and colleagues noted that in most circumstances people tend to orient their attention overtly, and as such propose a very tight relationship between eye movements and attention. They suggest that the same premotor mechanisms are involved in the planning of eye movements as orienting attention, and that in cases of covert attention the planned motor program is suppressed. In other words, covertly attending to a location is the same as programming a movement to said location and vice versa. This coupling of attention and motor programming has been come to known as the *premotor theory of attention*. The way it explains the cost observed when the target appears on the invalidly cued hemisphere is that this prompts a cancellation of the previous motor program and requires the reprogramming of a different oculomotor plan involving different muscles. The smaller effect observed for invalidly cued trials in the same hemisphere are due to fewer changes being required to the motor program.

Although the work by Rizzolatti et al. (1987) investigated the meridian effect observed in eye movements, and the literature on the premotor theory often tends to focus more on the relationship between attention and saccades, the premotor theory was subsequently extended to other effectors as well. Rizzolatti and colleagues point out that space is represented in separate pragmatic maps for different effectors, where the respective actions are computed (Rizzolatti, Riggio, & Sheliga, 1994; Sheliga, Riggio, & Rizzolatti, 1995). Indeed, as we shall see in the course of this chapter, several of the phenomena observed with regards to eye movements that could be taken to support the premotor theory are also observed in manual

movements. To re-iterate, according to the premotor theory, attention and action are linked by the fact that the orienting of attention and planning a movement are one and the same process. We will now take a look at the VAM, which proposes a different mechanism through which attention is linked to movement planning.

2.3 The Visual Attention Model – An Overlooked Alternative?

The VAM takes a different approach for explaining the link between attention, perception and action. There is ample evidence of broadly two separate visual processing streams in the brain, a dorsal one which focuses on using visual information to guide actions, and a ventral stream focused on object recognition (Goodale & Milner, 1992; Milner & Goodale, 1995). This framework of visual specialisation can lead one to loosely divide visual selection into selection-for-perception (SfP) in the ventral stream, and selection-for-action (SfA) in the dorsal stream (e.g. Sandoval Similä & McIntosh, 2015). Although these two streams do interact with one another (Schenk & McIntosh, 2010), it is a useful framework for understanding where attention may step into the equation, i.e. before the split of visual processing into the two streams.

According to the VAM, attention acts on and enhances the processing of an *object token* represented in V1. The object token itself consists of a location-specific and object-based "visual chunk" consisting of a collection of visual features, which has been selected by the either exogenous or endogenous orienting of attention (see section 1.4 for a distinction between the two). The tagged features of this object token are then processed further along both visual streams: the features pertinent to SfP are processed further along the ventral stream and the features pertinent to SfA receive prioritised processing along the dorsal stream. In other words, regardless of the initial behavioural goal for which said object token is processed, the consequences are felt along both streams. For instance, if a stimulus was selected for a perceptual discrimination task processed by the ventral stream, this would result in it also being processed along the dorsal stream, and vice versa. Conversely, attentional inhibition of

the object token of a visual distractor would result both in the inhibition of the perceptual representation of the object in the ventral stream, and in the inhibition of any actions towards it in the dorsal stream. In this framework SfP and SfA are both mandatorily coupled to one another, and one cannot occur without the other, as attention acts upon a shared visual representation.

There is neural evidence which is consistent with some of the underlying mechanisms proposed for the VAM. For instance, several papers have found attentional effects in V1 areas, which support the involvement of attention in early visual areas (e.g. Kastner, Pinsk, De Weerd, Desimone, & Ungerleider, 1999; Poort et al., 2012; Roberts, Delicato, Herrero, Gieselmann, & Thiele, 2007; Watanabe et al., 2011). Furthermore, Schneider hypothesised that the different features are tagged as being part of the same object via synchronous neural firing, a mechanism that has been deemed key in tagging different features belonging to the same object. This binding issue is beyond the scope of the present work, but for a for a review see Singer (1999).

We are about to review a series of behavioural studies which support a close link between attention and movements, much of which support both the premotor theory and the VAM. In fact, the main difference between these two frameworks is not so much that they produce very different predictions, as they are in fact quite similar, but a conceptual one. Both propose a coupling between SfA and SfP, but the way in which they are linked is different. Schneider and Deubel (2002) explain the difference by stating that according to the premotor theory of attention spatial allocation of attention is a consequence of a planned movement, while according to the VAM a movement is planned due to the preceding attentional allocation. Nevertheless, this difference yields some different predictions between the two frameworks. For instance, according to the premotor theory of attention, not being able to plan a movement to a location would prevent one from also attending to it, while the VAM has no such limitations. Furthermore, the premotor theory also implies that as they are one and the same

process, motor planning is the key determinant of how attention is allocated. In contrast in the VAM the object token is determined by several factors, of which the motor movements are but one of many factors. Which of the two theories may fit better with the existing data will be returned to in section 2.6.1 (p. 65), but also from the experiments conducted in the course of the present thesis.

2.4 Attention and Saccades

If one were to ask a person on the street to describe a movement, the first one that will come to mind will probably not be saccades. However, they are the most frequent movement we make, and are tightly coupled with attention. This can be seen both in presaccadic attentional enhancement at the location of an upcoming saccade, as well as in the curvatures of the trajectory. Evidence on for both of these phenomena shall be now reviewed, together with what they tell us.

2.4.1 Presaccadic Shifts of Attention – Action provides clarity

If one of the purposes of attention is to guide movements, then one would expect attentional enhancement at the target location to precede the movement itself, and there is ample evidence that this is indeed the case. One of the earliest demonstrations of this was conducted by Shepherd, Findlay and Hockey (1986), who found that participants were faster in responding to a stimulus when it appeared either at a likely location, or at a location that was about to be saccaded to. When the saccade target and the likely location of the stimulus did not match, the saccadic target location elicited the stronger enhancement, providing one of the first indications that saccade preparation induces mandatory shifts of attention. One influential study which followed was conducted by Deubel and Schneider (1996), who found subjects had improved perceptual discrimination at the location they were about to perform a saccade to. Subjects had to perform a saccade to one of three targets on either side of a central cue as fast as possible, and preceding the execution of the saccade a probe (an E or a digital 3) briefly appeared (120ms) at one of the possible target location. At the end of the trial participants had

to report which of the two probes had appeared. In this case attentional allocation was measured by the accuracy with which the probe, also known as the discrimination target (DT), was identified, the assumption being that its identification would be better if it appeared at a location coinciding with the focus of attention.

The identification of the DT was indeed heightened when it appeared at the saccade target location. In order to confirm that this attentional enhancement was tied to the upcoming movement, Deubel and Schneider carried out a subsequent experiment where participants were told in advance the location at which the DT was going to appear. However participants had above chance DT-discrimination performance only when its location was also the target of the upcoming saccade, thus indicating that attention cannot be easily oriented to a location other than the movement target.

Similar findings were obtained by Kowler, Anderson, Dosher and Blaser (1995) and Hoffman and Subramaniam (1995), who also found attentional enhancement at the location of the saccade target even when the saccade target was known in advance. However Kowler et al. (1995) found that some attentional resources could be allocated elsewhere depending on the component of the task subject were told to prioritise: the saccade execution, the perceptual task, or both equally. Unsurprisingly in the first case attention was more tightly coupled to the saccade task, and in the second covertly attending to a separate location resulted in longer saccade latencies, implying the involvement of oculomotor processes in both cases. In the last condition people did manage to disengage *some* of their attentional resources away from the saccade target and to the known location of the appearance of a DT, though the majority of attentional allocation was still directed to the saccade target. This suggests that not all of VSA resources are necessarily tied to the saccade target, though its location is prioritised. However, these findings should be interpreted with care, as the different experiments were run on only two subjects, one of which was Kowler herself. Furthermore, practice effects may also have played a role, as the third condition was tested in the fourth experiment in the paper.

Nevertheless, there is more recent evidence suggesting that under the right circumstances VSA is not always confined to the saccade target. It is important to bear in mind that presaccadic attentional facilitation is not instantaneous or binary, but increases gradually and peaks at 150-200ms after the cue onset (Castet, Jeanjean, Montagnini, Laugier, & Masson, 2006; Montagnini & Castet, 2007). With this in mind, Montagnini and Castet (2007) found that although attentional enhancement provided the largest benefits at the saccade target, and that this happened at 150ms after cue onset, some attention could still be allocated to the likely DT location, even when it was in a diametrically opposite location. Performance at this location was not as high as performance at the saccadic target at its peak, and it was stronger for participants who had received more training, but it demonstrates that not all VSA is allocated to the saccadic target, and that endogenous attention may act independently from presaccadic facilitation. The benefits of advance knowledge on allocating attention away from the saccade target has also recently been reported not only with regards to knowledge of the spatial location of the discrimination target, but the colour as well (Born, Ansorge, & Kerzel, 2013). These results could be due to a second saccade being planned in parallel, as we have seen in the previous chapter (e.g. Baldauf & Deubel, 2008; Gersch et al., 2004; Godijn & Theeuwes, 2003), but resulting in a smaller amount of enhancement due to the first location being prioritised. This is a possibility, but a somewhat speculative one. A perhaps more plausible explanation is that the relationship between VSA and motor programming is weaker than the results from Deubel and Schneider would lead us to believe (1996). This point is further validated by another recent paper which found that attention can be allocated to a non-saccade target when validly cued (Moehler & Fiehler, in press). Subjects were cued both the likely location of a DT and a saccade target, and perceptual performance was highest when these two coincided, although it was still above chance when they did not. Interestingly, motor performance was also influenced in a similar way, in that saccade accuracies were higher when both cues were congruent with one another. In incongruent trials saccade trajectories veered away from the DT-location, suggesting the inhibition of a saccade plan to the covertly attended

location. We will take a closer look at saccade trajectories and what they tell us in section 2.4.3 (p. 48).

While these studies suggest that contrary to the findings by Deubel and Schneider (1996), not all attentional resources are allocated to the saccade target, the studies we have reviewed in this section so far are consistent with the general idea that SfA results in SfP. Nevertheless there is work which suggest that motor planning is not always sufficient or required for perceptual enhancement. An early example of such work was from Klein (1980). Though its findings may derive from methodological issues, a closer look at his study and the criticism it received provides some interesting insights into how presaccadic attention relates to the point in time a saccade is executed.

2.4.2 Klein (1980) and presaccadic attention shifts

In 1980, Klein conducted two experiments investigating the relationship between the preparation of saccades and attention, and what he dubbed the *oculomotor readiness hypothesis* (Klein, 1980). The oculomotor readiness hypothesis stated that saccades to a covertly attended location would be facilitated, and that conversely attentional resources would be allocated to an upcoming saccadic target. Both predictions are similar to those made by the VAM and the premotor theory, yet Klein failed to find support for either one. Although this can be attributed to the methodological details of Klein's experiments, his findings are still useful in elucidating the role motor movements play in attentional allocation.

In his first experiment, Klein had participants perform a saccade to a target either to the left or right of fixation when an asterisk appeared on the screen. The asterisk could appear at location of either peripheral target, but the saccadic target would remain the same for the duration of the block. This meant that the asterisk would coincide with the location of the saccade target on half of the trials, and be at the opposite location on the other half. However on some trials, no asterisk would appear and instead one of the two peripheral targets would briefly brighten,

in which case the participant had to manually respond to the event. The assumption was that since the saccade target was kept constant, participants were continuously 'ready' to perform a saccade to the target, and were merely waiting for the asterisk to perform it. Thus the RTs of the manual responses to the brightening of the peripheral stimulus would be faster when it coincided with the stimulus participants had to perform a saccade to during that block of trials. This was not the case.

The second experiment was very similar to the first, with the exception that participants primarily had to attend to one of the stimuli for the duration of the block and monitor for a luminance change, and only on some trials would an asterisk appear, and the participants would have to saccade to the location the asterisk appeared at. This time the oculomotor readiness hypothesis predicted that RTs for the saccades would be faster when the saccade had to be performed to the attended location. Once again, the results did not support this hypothesis, as saccadic RTs to either the attended or unattended side did not differ significantly from one another. In other words, these results would initially seem to suggest that neither the preparation of a saccade enhance perceptual performance (Experiment 1), but neither did covert attention facilitate subsequent saccades (Experiment 2), although Klein does not deny that these may nevertheless still be tightly linked.

However Klein's experiments have methodological issues which should caution one against his conclusions. For instance, Hoffman and Subramaniam (1995) pointed out that for both experiments the task which was done less frequently (discrimination of the brightening of a stimulus in Experiment 1 and performing saccades in Experiment 2) may have not been prioritised by the participants, and only been performed after the most common task. However perhaps the main problem with Klein's interpretations stems from the assumption that participants in either experiment were constantly ready to execute a saccade, whereas there is no way of knowing whether this was actually the case (Rizzolatti et al., 1987; Hoffman & Subramaniam, 1995). In fact, this seems unlikely. For instance, Smith and Schenk (2012) point

out that the participants' relatively high mean saccadic RTs (> 340ms) suggests that the saccades were not being programmed in advance and were merely waiting to be released.

This inference becomes more plausible when one considers the study by Deubel and Schneider (2003) which instructed participants to carry out a manual movement or a saccade at different delays, as well as being told in advance the location of an upcoming discrimination target (DT). They found that if participants performing the manual movements were given enough time, when there was a mismatch between the movement target and the location of the DT, participants would perform well in the perceptual task. This meant that during the delay they could first allocate attention to the manual movement target and then then allocate their attention to the location of the upcoming DT, and eventually executing the manual movement would not reallocate resources to the movement target. This was not the case for participants conducting the saccadic version of the experiment. For them, regardless of the amount of delay between the indication of the saccadic target and the instruction to execute the saccade, performance in the discrimination task was poor when the DT did not appear at the saccade target location. This suggests that for saccades, but not manual movements, attentional allocation is tied closely to the point in time it was executed. In other words, contrary to Klein's initial assumption (1980), saccade planning is not sufficient without it being closely followed by saccade execution. Furthermore, recent work by Belopolsky and Theeuwes (2012) found that contrary to the findings by Klein (1980), covert attention did enhance saccade execution to that location, provided the saccade was executed shortly after the attention was shifted there. Delays in execution of even 200ms appeared to suppress the facilitation, which would also help explain Klein's results. This once more seems to tie perceptual enhancement and saccade execution closely in time.

Further support for this comes from a recent study by Born, Mottet and Kerzel (2014). In their experiment participants were presented with two potential saccade targets, and participants were then presented with an arrow at fixation which instructed them which target to saccade

to. Participants were to make the saccade as quickly as possible, but also report the identity of a DT (i.e. whether an asymmetric plus sign had the vertical line to the left or right of centre). The DT appeared at the saccade location on half of the trials. In these details the experiment has been quite similar to previous work (e.g. Deubel & Schneider, 1996), but the novelty of this study was that on one third of the trials, after the saccade target had been cued but before the DT was presented, participants were then presented with an auditory beep. This instructed participants not to execute the saccade. The time of the beep was calibrated for each participant so as to yield to a successful cancellation of a saccade on 50% of these trials. For these stop-trials, Born and colleagues found perceptual enhancement at the saccade target only on the ones where the saccade was not successfully inhibited. They interpret these results to indicate that presaccadic enhancement is only found in instances in which a saccade is executed. However, as the DT always appeared after the instruction to cancel the saccade, another way of framing these results is that pre-saccadic attention shifts only occurred in cases in which the saccade was not successfully cancelled, and thus saccade preparation was still ongoing when the DT was presented. This would be consistent with the results by Montagnini et al. (2007), who found that the allocation of attention gradually increased before execution, reaching its peak around 150-200ms into saccade preparation. If the saccade is cancelled too early in this process, no enhancement will have had time to accrue at the saccade target. The role of saccade execution is further strengthened via another study conducted by Born and colleagues (Puntiroli, Kerzel, & Born, 2015), who subsequently found perceptual enhancement at the upcoming targets of saccades made to incorrect locations.

Though these experiments show that attentional enhancement is tied closely to the point in time in which a saccade is initially planned to a location, this does not mean that both processes are one and the same, as would be suggested by the premotor theory (Rizzolatti et al., 1987). In fact, patient work would suggest otherwise. Work by Khan et al. (2009) found that one optic ataxia patient had unimpaired saccadic performance to his damaged visual field while his

presaccadic enhancement was impaired, thus dissociating motor preparation from presaccadic shifts of attention. Furthermore, Blangero et al. (2010) found a dissociation between presaccadic shifts of attention and covert attention: another optic ataxia patient displayed unimpaired presaccadic shifts of attention, but impaired covert attention within his damaged hemifield. These neuropsychological studies warn one against both equating presaccadic attention with motor planning (Khan et al., 2009) or as the only form of covert attention (Blangero et al., 2010). Instead, the former study implies that saccade execution and shifts of attention may share a common target selection, while the latter implies that covert shifts of attention do not always require saccade programming, but other orienting mechanisms. Both of these implications conform with the framework proposed by the VAM (Schneider, 1995), though one should be careful from overgeneralising the results from a small number of patients.

Klein's conclusions were led astray by his assumption that his participants were in a state of constant readiness to release a planned saccade. However his methods and results support latter work which highlights the role that presaccadic enhancement is closely tied to the point in time in which the saccade is executed (e.g. Belopolsky & Theeuwes, 2012; Born et al., 2014; Deubel & Schneider, 2003). Nevertheless, we can see already from neuropsychological work that one should be wary of assuming that covert shifts of attention require saccades (e.g. Blangero et al. 2010). We shall revisit this topic in more detail later in section 2.6.1 (p. 66).

2.4.3 Saccadic Curvatures – What we perceive influences how we act

If presaccadic shifts of attention are a good way of demonstrating how our actions influence the way we attend to our surroundings, deviations in saccadic curvatures illustrate the other side of the coin i.e. how what we attend to influences how we carry out our actions, i.e. SfP also influences SfA. Saccades to a target have repeatedly been shown to deviate towards (McPeek & Keller, 2001; McPeek, Skavenski, & Nakayama, 2000) or away (Doyle & Walker, 2001; Godijn & Theeuwes, 2002, 2004; Ludwig & Gilchrist, 2003; McSorley, Haggard, &

Walker, 2004; Sheliga, Riggio, & Rizzolatti, 1994) from distractors or other non-targets on a display. In other words SfP influences SfA, but how and why? To put it succinctly, saccade curvatures tell us important details about how attention is allocated in space, as well as the time course with which distractors are inhibited. We will go over three factors which have been shown to play an important role in determining the saccade trajectory before unpacking their implications for the underlying mechanism.

The first factor is how quickly a saccade is executed, also known as the saccadic reaction time or saccadic latency. It has been repeatedly shown that saccades with shorter latencies tend to veer towards the distracting stimulus, while saccades executed at longer latencies tend to veer away from the distractor (Laidlaw & Kingstone, 2010; McSorley, Haggard, & Walker, 2006, 2009; Mulckhuyse, Van der Stigchel, & Theeuwes, 2009; Walker, McSorley, & Haggard, 2006). This effect is illustrated in a simplified form in Figure 2.2 below (p. 50). McSorley et al. (2006) found that saccades stopped veering towards the distractor and away from it at latencies of around 200ms, thus indicating the involvement of a gradual but relatively slow process.

The spatial location of the distractor(s) in relationship to the saccade target is also an important component in determining a saccade's trajectory. For instance, McSorley et al. (2009) not only found that curvatures away from the distractor increased with time, these deviations were larger the closer the distractor was to the target. What may be more interesting however is what occurs in the presence of multiple distractors. McSorley, Haggard and Walker (2004) found that two identical distractors symmetrically placed on either side of a direct path between fixation and the saccadic target cancelled each other out resulting in a straight saccade trajectory. This suggests that the effects of the present distractors were somehow summed together. A more recent study by Sogo and Takeda (2007) carried out a similar experiment, but this time the distractors were not symmetrically located around the saccade path. If consistent with McSorley et al.'s interpretation (2004), this should have caused each individual

distractor to have an effect of different magnitude on the saccade trajectory depending on their location. This was indeed the case: the resulting curvatures when both distractors were present were equivalent to the summation of the curvature produced when each distractor was presented in isolation.

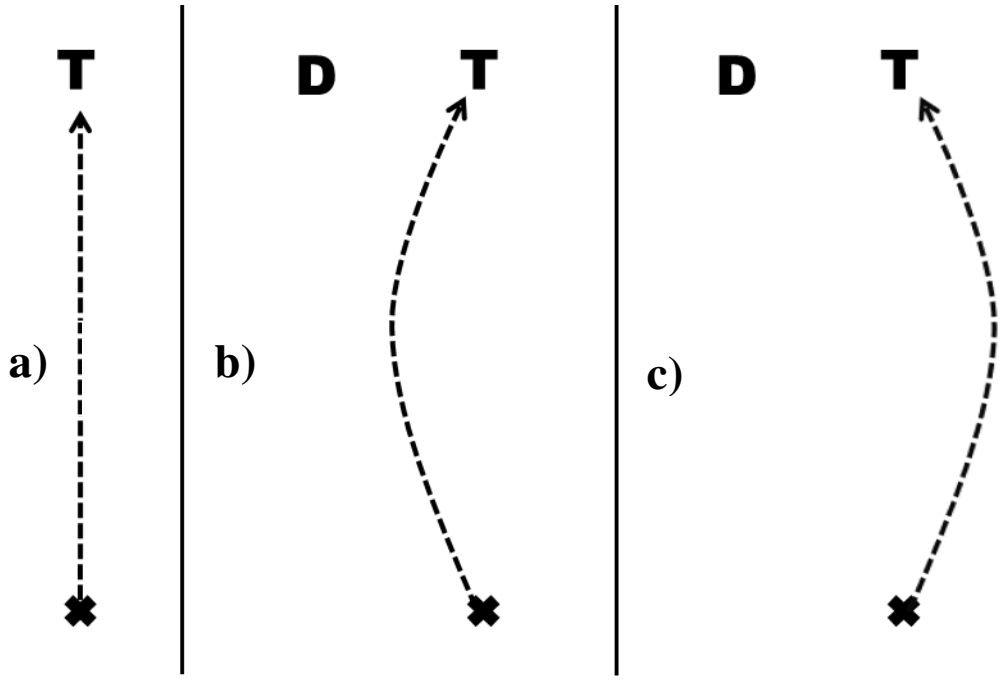

Figure 2.2. From left to right: a) a straight saccade path to the lone target; b) a quickly executed saccade veers towards a now present distractor, and c) a saccade with a higher latency veers away from the distractor, as seen in for example McSorley et al. (2006).

The third and final parameter influencing a saccade trajectory which we will discuss here is the nature of the distractor itself. First of all, the distractor needs to actually be a potential distractor in the first place. First of all, if the distractor is harder to perceive the effect this has on movement trajectories is smaller. Cardoso-Leite and Gorea (2009) utilised distractors presented at near detection threshold contrasts on participants asked to make a saccade to a target. The trajectory only deviated away from the distractors on trials in which subjects reported having seen the distractor. Van der Stigchel, Mulckhuyse and Theeuwes (2009) however did find that saccade curvatures could be influenced by a distractor presented so as to be only implicitly processed, but these curvatures effects were still much reduced compared

to when the subjects could successfully detect the distractor. In this other study the distractors contrast was not presented at near threshold levels, so this slight discrepancy in results might arise due to differences in reasons as to why a distractor was not perceived, such as only the former study utilising around-threshold luminance values (Deplancke, Madelain, Gorea, & Coello, 2013). Regardless, both of these studies are consistent in that they both indicate that stronger representation of the distractor (as measured by detection accuracies) leads on to larger curvatures. Similar effects have also been found with regards to distractor saliency, where the more salient the distractor, the greater its effect on saccadic curvatures (van Zoest, Donk, & Van der Stigchel, 2012).

Whether the distractor is visible or not however is not the only important feature, but the actual properties of distractors are also important. For instance the more similar the distractors are to the target, the more pronounced the effects on saccade deviations are (Al-Aidroos & Pratt, 2010; Ludwig & Gilchrist, 2003; Mulckhuyse et al., 2009). For instance Mulckhuyse et al. (2009) found that the more the distractor resembled the target, the saccades at lower latencies deviated away less from the distractors, but saccades executed at higher latencies deviated away more. If the distractor was more dissimilar, by for example not sharing the shape or colour with the target, the effect of latencies remained but were less pronounced. Once again, the saccade latencies are critical in influencing curvatures in modulating the effects of target-distractor similarity. But how do we interpret the different findings listed above, and what are the underlying mechanisms? As alluded to at the start of this section, inhibition plays a considerable part in explaining these phenomena.

Saccade plans are made to the different stimuli that could be processed as saccade targets. However, most stimuli in our environment are not pertinent to our behavioural goals, such as the distractors in the experiments covered above. Therefore the task-irrelevant saccade plans need to be inhibited, which leads to veering away from the irrelevant location. This inhibition takes time to be applied, which explains what we have seen above. Saccades with shorter

latencies lead to veering towards the distractor due to the saccade plan to it not having been fully inhibited yet, and as the saccade latencies increase so does the amount of inhibition applied to the saccade plan to the distractor, leading to veering away. It is worth mentioning that locations where a distractor is expected to appear can also be inhibited in advance. It has been found that saccades veered away from predictable distractor locations even on trials where the distractor is not ultimately presented (Van der Stigchel & Theeuwes, 2006).

This may explain why the saccadic latencies are an important factor, but it does not address the more fundamental issue as to why these competing action plans result in curvatures in the first place. As we saw in the work on the spatial location of multiple distractors (McSorley et al. 2004, Sogo & Takeda, 2007), the curvatures appear to be products of the summing together of the vectors of the different actions plans. Each action plan is represented by different population of neurons, and the summation of them determines the initial saccade trajectory. The role of population coding has been present in the literature for at least over 15 years (Tipper, Howard, & Jackson, 1997; Tipper, Howard, & Houghton, 2000, see also section 1.8 p. 32), and explains the saccadic curvature phenomena well. Not only does it coincide well with what we have seen with regards to the spatial distribution of stimuli, but it also provides a useful framework within which to understand the time course of these trajectory deviations: when you sum together the vector coding for a distractor location which has not had time to be inhibited with the vector coding for the target, you get veering towards the distractor. However when more time has passed and the distractor is actively inhibited, this results in a 'negative vector' towards that location, which when combined with the target vector results in trajectories veering away from said location. Similarly, the more salient a distractor, the stronger the resulting saccade plan towards it, accounting for example for the data by Cardoso-Leite and Gorea (2009). Furthermore, the higher the saccade target-distractor similarity, the longer it takes for the distractor to be identified as such, and more inhibition is required to eventually solve the conflict (e.g. Mulckhuyse et al., 2009).

There is neurophysiological evidence supporting the population coding account, and the superior colliculus (SC) is believed to be a crucial site for where this competition takes place (McIlwain, 1999; McPeek, Han, & Keller, 2003; McSorley et al., 2004, 2006; Schneider & Kastner, 2005; Shen & Pare, 2014; Sparks, Rohrer, & Zhang, 2000). The SC is located in the brainstem, and consists of two hemispheres, each coding for the contralateral side of space (DuBois & Cohen, 2000; Gandhi & Katnani, 2011; Schneider & Kastner, 2005). The findings of McPeek and colleagues in particular make a strong case for the SC as the site of this competition (McPeek et al., 2003). They found that the amount of activity at the distractor site (but not at the target location) preceding saccade onset correlated with the amount of curvature towards the distractor. Correlation does not equal causation, but they then went further than merely recording SC-activity: they then presented a lone saccade target, and stimulated the locations which matched the distractor sites in the previous set of experiments. They found that the higher the stimulation frequency, the more the saccade would deviate towards the stimulated site. A detailed review of the neurophysiological literature is beyond the scope of this thesis, but McPeek et al.'s work neatly aligns with a population theory account, which in turn explains well the data covered so far. For more extensive reviews on saccadic curvatures see Van der Stigchel, Meeter and Theeuwes (2006) and Van der Stigchel (2010).

It is worth noting that the SC is also implicated in the orienting of attention itself (Ignashchenkova, Dicke, Haarmeier, & Thier, 2004; J. Müller, Philiastides, & Newsome, 2005). Ignashcenkova et al. (2004) found that visuomotor neurons, i.e. neurons that fire both in response to visual stimulation as well as motor programming, were activated both in overt and covert attention tasks, thus supporting the involvement of the SC in attentional orienting. These are located in the intermediate layer of the SC, which has been implicated in saccade target selection. Again, correlation does not imply causation, but as we saw above, microstimulation again helps to strengthen a causal link. Müller et al. (2005) found that stimulating the spatial map in the SC increased the discrimination accuracy for stimuli

presented during a covert attention task at the spatially matching location. The SC is thus not only closely linked with saccade generation itself, but also orienting of attention without saccades. A neural structure involved in both processes helps render a close link between SfP and SfA more plausible.

Are there any practical consequences of curved saccade trajectories? It is possible that waiting for the competition to be completely resolved between action plans before executing a saccade, results in unnecessary time costs, considering the few, if any, practical disadvantages of executing curved saccades. They tend to be as accurate as non-curved ones, and at any rate typically only accurate saccades are included in curvature analyses (e.g. Ludwig & Gilchrist, 2003). However there is another possibility, which is that similar processes are guiding not only saccades, but manual movements too, in which case summing movement vectors has the added benefit of resulting in the moving hand avoiding physical obstacles. It is possible that while these saccadic curvatures bear no discernible costs, manual curvatures may lead to advantages, however slight. We will now proceed to explore the role of VSA in the guidance of manual movements, which we shall see bears both many similarities with the relationship of attention and saccades, but also some marked differences.

2.5 Eyes and Hands – Same or different?

We have so far seen that attention and eye movements are linked, but in order to make the claim that the role of attention is to guide action, one must bear in mind that eye movements are not the only ones that we execute, even though they may be the most frequent ones. One of the most common motor effectors that we utilise after our eyes are our hands, so the question one must ask is whether attention is also tied to the execution on manual movements. Do we see the same phenomena with hands as we see with saccades? The short answer is that this is indeed the case, although there appear to also be some effector specific differences which we will look at in section 2.5.3.

2.5.1 Pre-movement shifts of attention

Although the relationship between manual movements and attention has been less studied than the link between saccades and attention, there is still considerable literature on the subject. One of the earliest tests of whether manual movements would elicit similar effects as saccades was carried out by Deubel, Schneider and Paprotta, (1998), who essentially conducted the same experiment as Deubel and Schneider had run a few years earlier (1996), only this time they had participants maintain fixation in the centre and they had participants point at the indicated target. Like in their saccadic experiment, DT discrimination was best at the location of the target, although this time they did not test whether any attention could be allocated in parallel to another location than where the target appeared. However, other evidence seems to suggest a strong link to the pointing location. For instance, Linnell, Humphreys, McIntyre, Laitinen, and Wing (2005) demonstrated that covert object-based attention effects were superseded by the execution of a pointing action. They found that previously observed object-based effects of covert attention in a passive (i.e. no movement) condition disappeared when participants had to perform a pointing movement. Attention was directed at the pointing target, and discrimination of the DT did not differ between other locations within the object or outside of it. This suggests that attention for action guidance has priority over object-based attention, and thus strengthening the claim that the former is one of the main purposes of VSA.

Similar effects can be seen in actions beyond ordinary pointing. In a manner analogous to saccades (Baldauf & Deubel, 2008a; Godijn & Theeuwes, 2003), multi-step pointing movements have been shown to elicit attention shifts in parallel to two or even three locations with little or no cost in perceptual acuity at the different locations (Baldauf et al., 2006; Deubel & Schneider, 2004), provided in both cases that the movements are executed in quick sequence (Baldauf, 2011; Gersch et al., 2004) (See Figure 2.3 for an illustration of this). Similar findings of multiple attentional foci have also been reported in single-movement pointing movements executed with both hands to separate locations (Baldauf & Deubel, 2008b). The apparent

recruitment of extra attentional resources to so many locations with little or no cost is startling considering our limited attentional capacity, and we shall be returning to this in more detail from Chapter 5 onwards.

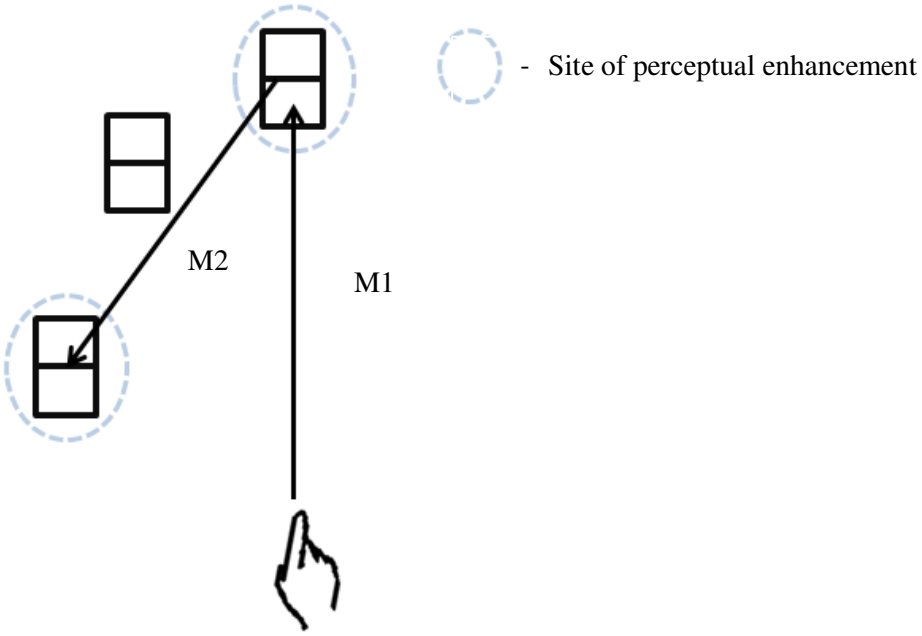

Figure 2.3. Illustration of perceptual enhancement being induced in parallel at the target of the first (M1) and second (M2) movements of a multi-step pointing sequence before the onset of the first movement (e.g. Baldauf et al., 2006).

However, other manual movements such as grasping have also been demonstrated to show parallel allocation of attention to the locations in which the grasping fingers were going to contact the object (Deubel & Schneider, 2004; Schiegg, Deubel, & Schneider, 2003). In both studies, subjects had to grasp a wooden 'X' between their index finger and thumb. If subjects were reaching with their left hand their thumb would be placed at the bottom right branch of the 'X' and their index finger would be placed onto the top left branch. If subjects reached with their right hand, the equivalent but mirrored movement would be made, with the right thumb being placed onto the bottom left branch and the index finger onto the top right branch. Attentional allocation was measured by the correct identification of the DT (again an 'E' or a '3' as in Deubel et al. (1996)), and therefore the 'X' itself was surrounded by 16 mask-items

at which the DT could appear. DT discrimination was best when it appeared at the ends of the branches by which the 'X' was being grasped. Analogous to the findings by Deubel and Schneider (1996), Schiegg et al. (2003) found that advance knowledge of the DT target did not improve performance when it did not match a location being grasped.

When Deubel and Schneider investigated the paradigm further (2004), they found that this effect was modulated by object based attention. In one of their experiments they replaced the X with two overlaid rectangles with the same combined contours (see Figure 2.4). Instead of probing the then ends of the objects, they instead had the DT appear in the middle of the figure. Detection of the DT was enhanced only when the DT was perceived to be appearing on the rectangle being grasped i.e. the one on top. If the enhancement was purely based on spatial location of the DT, the detection accuracy should remain the same regardless of which rectangle was being grasped. Unfortunately in this experiment Deubel and Schneider did not probe the ends of the branch, so one can only assume that attention was still being directed at the points being grasped as in the previous experiments. However it demonstrates that attention in an action-context is still susceptible to object based modulation. It is important to remember though that there is still a spatial component, as if the whole object was selected then the previous experiments utilising an 'X' would have found facilitation at all branches of the object rather than just the points being grasped.

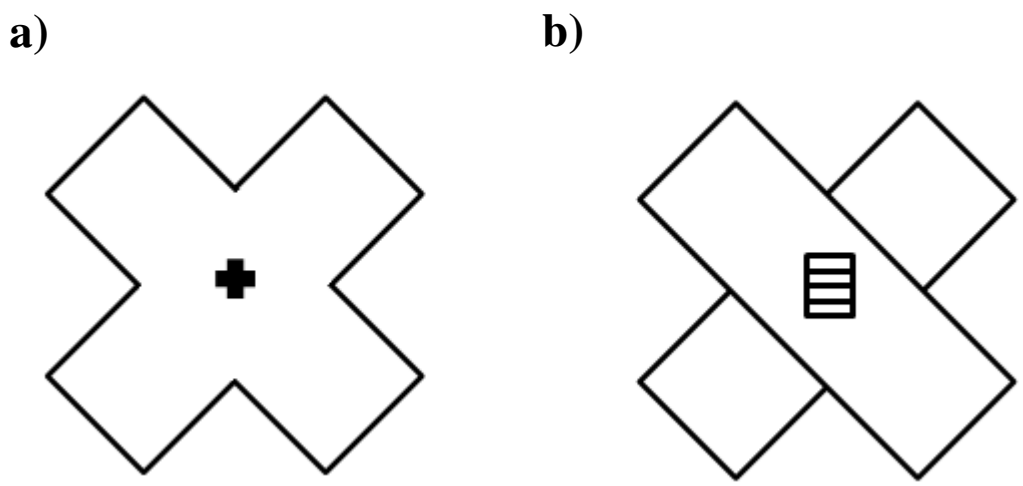

Figure 2.4: Comparison of the objects to be grasped in the experiments carried out by Schiegg et al. (2003) and Deubel and Schneider (2004). a) The 'X' with a fixation point in the middle, as used in the work by Schiegg et al. and Deubel and Schneider's Experiment 1. The 16 surrounding masks are not shown. b) The object to be grasped in Deubel and Scneider's Experiment 2.

So far these experiments strongly suggest that attention is allocated to a manual target in a similar way as it is to a saccadic one, even in the case of more disparate actions such as grasping. In other words: once more, SfA is seen to influence SfP. Is the converse still true? There is evidence suggesting that this may still be the case. For instance, the maximum grip aperture to a target has been shown to be influenced by the size of another stimulus present in a concurrent perceptual task. Castiello (1996) demonstrated this by asking subjects to grasp for a piece of fruit they were fixating on. Subjects were also given a concurrent task in which they had to count the number of times a peripheral and covertly attended separate fruit was illuminated. The size of this peripherally attended fruit was found to influence the maximum grip aperture of the actions to the central fruit. For instance, if the fruit to be reached was an apple and the peripheral fruit to be counted was a cherry, this would result in a smaller grip aperture than if the fruit to be counted was either absent or of a larger size. A concurrent perceptual task at a different location has also been shown to not only impair grasping performance at an alternative location, but also the perceptual task itself, suggesting that both are tapping to the same attentional resource, although the perceptual task can be prioritised

over the motor task (Hesse & Deubel, 2011; Hesse, Schenk, & Deubel, 2012). We shall see that curvature data is also consistent with this view.

2.5.2 Manual trajectories

Manual trajectories show essentially the same patterns as saccades, with reported cases of manual movements veering either towards (Song & Nakayama, 2006, 2008; Welsh, Elliott, & Weeks, 1999) or away from distractors (Howard & Tipper, 1997), and in some cases both (Tipper et al., 1997; Welsh & Elliott, 2004). Once again, this appears to be tied to competing motor plans, and the amount of inhibition that has had the time to be applied on the non-target, as movements with faster RTs veer towards the distractor and later ones veer away (Welsh & Elliott, 2004). Another case in point suggesting that curvatures reflect the amount of inhibition applied to non-targets is that the distance between the distractor and the target influences whether the trajectory veers away or towards the former (Tipper et al., 1997). Distractors further away, which are less likely to be obstacles, induce less inhibition and as such movements veer towards them, while closer distractors are 'avoided' and trajectories veer away. This is reminiscent to the role of spatial location of distractors in influencing saccade curvatures (e.g. Sogo & Takeda, 2007). Furthermore, the detectability of the distractor also has similar effects on manual curvatures as those we have seen for saccades (e.g. Cardoso-Leite & Gorea, 2009). In a fashion similar to Cardoso-Leite and Gorea, Deplancke et al. (2010) found that the less detectable the distractor, the smaller the deviations towards the distractor. Furthermore, when two distractors were presented at symmetrical locations, as we have seen with saccades (p. 49), these appeared to cancel each other's influence resulting in straight movement trajectories. It is worth noting that participants were trained to produce speeded manual responses resulting in low movement onset latencies, which is why the trajectory deviations, when observed, occurred towards the distractor.

Differing amounts of inhibition to different spatial locations is in itself not surprising, as obstacle avoidance is crucial for successful manual movements, and obstacles in different

locations have shown to affect trajectories in different ways, depending on the obstacle's location (Mon-Williams, Tresilian, Coppard, & Carson, 2001). In fact, obstacle avoidance is so ingrained that it occurs both in cases in which the target changes location during a movement and a previously unobtrusive object suddenly becomes an obstacle (Chapman & Goodale, 2010), but also in patients who are not aware of the obstacle itself (McIntosh, McClements, Dijkerman, Birchall, & Milner, 2004). These findings on obstacle-avoidance highlight the main difference between manual movements and saccades, which is that hands move in external space whereas eyes do not. We shall now explore some of the consequences this crucial difference has.

2.5.3 Time and Space – Differences between the effectors

Although we can covertly attend to different locations, our attentional shifts tend to be overt, in that they tend to be accompanied by eye movements, and as stated above both eye movements and shifts of attention have been linked with activity of the SC (e.g. Ignashchenkova et al., 2004). Considering our propensity to make overt shifts of attention, and with little cost of executing oculomotor movements, a close neural link between saccades and at least some forms of attentional orienting is conceptually sound. Nevertheless, the SC has also been implicated in manual movements. Distinct neurons in the SC have been linked with reaching, which are intermingled with but separate from visuomotor neurons or neurons related to saccade execution (for a review see Gandhi & Katnani, 2011). Furthermore, Song, Rafal, and McPeek (2011) found that inhibition of the primate SC inhibited target selection for reaches as well as saccades, when multiple stimuli were presented. When a target was presented alone the motor execution of reaches was unaffected, albeit saccade execution was still impaired. This leads one to conclude that the SC may also have a general role in target selection, regardless of the movement effector (Krauzlis, Lovejoy, & Zénon, 2013). However, if manual movements were as tightly bound to the way in which we oriented attention, this would result in our hands moving around our environment with our shifts of attention, and

likewise our attention would be shifted with our movements all the time. Typing this manuscript would be a lot slower and challenging if each key stroke would hijack the writer's attention in the same way saccades do.

The way in which memory-guided pointing differs from memory-guided saccades illustrates this point neatly (Deubel & Schneider, 2003). What Deubel and Schneider found was that presaccadic facilitation was tied to the time point in which the saccade was executed, no matter how much in advance the saccade was planned, while for pointing the facilitation disappeared for delays of 300ms or larger. For pointing, participants could focus their attention and plan their movement, and then carry it out 'offline' later without re-engaging attention, while in the case of a saccade a shift of attention always immediately precedes it. In line with this, manual movements have recently been shown to rely more on visual short term memory for action guidance than saccades (Issen & Knill, 2012). These different findings might explain why Bonfiglioli, Duncan and Rorden (2002) failed to find facilitation at the site of a pointing movement: in their experiment participants had to point either to a target in front of the left hand or to a target in front of the right hand, with each one respectively. With such few movements required, the task could easily be done from memory, without the recruitment of attention following the initial trials.

There is also work showing that attention can be allocated simultaneously both to the target of a saccade and a pointing movement. Jonikaitis, Schubert and Deubel (2010) found that although the actual reaction times of the movements were slowed down by having to plan both types of movements, the speed at which attention itself was oriented to both locations was not. Similar findings were subsequently obtained by Jonikaitis and Deubel (2011), albeit the time course for attentional allocation to the pointing target was slightly slower. Jonikaitis and Deubel (2011) interpreted their findings to demonstrate that each type of movement taps on to separate attentional resources. One reason why they reach this conclusion is that when both a saccade and pointing movement are targeted to the same location, DT discrimination

performance increases to above the discrimination rate displayed when only a saccade or pointing action was executed. This result could be explained by an additive effect of different attentional systems acting at the same location. Though possible, this effect could equally be explained by the *same* attentional system allocating resources to separate pragmatic maps of the different effectors independently (e.g. Itti & Koch, 2000), and which again are summed up when the targets for both effectors match. In other words, one does not need to invoke separate mechanisms to explain an additive effect. DT discrimination performance may be better when both effectors are acting on the same target than when only one movement is being performed, but this could be due to not all of the available attentional resources being allocated in a single-effector movement task, even if performance levels were not at ceiling. Not all attentional allocation is under volitional control, and after all enough attention was allocated for the movements to be executed accurately, which was arguably the primary task of the participants. Furthermore, more recent work by Khan, Song, and McPeek (2011) failed to find improved discrimination performance when both a manual and saccadic response was executed to the same location, which also suggests a shared attentional resource between effectors. They attribute their findings to having a harder perceptual task than the one used by Jonikaitis and colleagues (Jonikaitis & Deubel, 2011; Jonikaitis, Schubert, & Deubel, 2010), as the DT target could be one of four stimuli rather than just two. It therefore appears that although VSA can be allocated independently to different effectors, they have a shared underlying attentional source.

Another, less controversial, difference between saccades and manual movements is that whereas the former are generally assumed to be ballistic, in that their trajectories cannot be changed mid-execution, the same does not apply for controlling our hands (although see Gaveau, Martin, and Prablanc (2003)). As we have mentioned above, this is useful both for the avoidance of obstacles, but also for updating our motor plan if the target changes location. This process has been shown to be, to at least some extent, automatic, with participants often

correcting their movements to the new location even when instructed not to (Pisella et al., 2000; McIntosh, Mulroue & Brockmole, 2010). Furthermore, people have also been shown to correct their movements when the target was displaced during a saccade, i.e. during saccadic inhibition. Not only did the jump occur when the visual input was being suppressed, but the target was no longer present by the end of the saccade, thus resulting in participants lacking awareness of the target jump (Cameron, Enns, Franks, & Chua, 2009). Nevertheless, even these automatic corrections rely on attention for their action guidance. Sandoval Similä and McIntosh (2015) found that carrying out a concurrent covert attentional task had a detrimental effect on online corrections. Subjects had to execute a pointing movement to a centrally located target, while concurrently covertly monitoring one of two lateral flankers. On some trials the target would jump to one of the flanking locations at movement onset. In such jump-trials subjects were to correct their movement onto the new target location. The flankers consisted of a small grey square (0.14°) on either side, one of which could disappear for 20ms. Subjects knew in advance which flanker could disappear, and this was altered between blocks. At the end of the trial subjects had to report whether the pertinent flanker had 'flickered' or not. One of the key findings of this experiment was that the concurrent perceptual task (i.e. flicker-monitoring) decreased the overall rate of online corrections, compared to a previous experiment where the lateral monitoring occurred before the movement onset. Furthermore, corrections were less likely to be executed if the pointing target jumped onto the covertly attended location. Covertly attending to a location appeared to not only result in inhibition of eye movements to said location, but also pointing movements. These results would conform with the view of VSA resources being shared by different effectors (Hesse & Deubel, 2011; Hesse et al., 2012).

This contrasts previous findings by Liu, Chua and Enns (2008), who found that manual online corrections were unimpaired by a concurrent perceptual task. This discrepancy may be accounted for by the relative ease of the secondary perceptual task used by Liu et al. (2008),

as indicated by almost ceiling performance of their participants (mean accuracy of 96.5%, compared to 78% in the study by Sandoval Similä and McIntosh (2015)). Online corrections show a high level of automaticity (McIntosh, Mulroue, & Brockmole, 2010; Pisella et al., 2000), and as such the attentional demands of a simultaneous perceptual task have to be high enough for a cost to be visible, a condition not met by Liu et al. (2008).

We have already seen that shifts of attention tend to be saltatory (e.g. Chastain 1992a, 1992b; Remington & Pierce, 1984), and the visual processing of the information during a saccade itself is suppressed (Matin, 1974). However for manual movements, is only the end point attended to? Considering what we have seen about the role of obstacle avoidance in the guiding of actions, that the movement path would not be attended to seems unlikely, even if a manual movement can be programmed in advance. Attentional allocation to other parts of a movement has not received much scrutiny, but recent work has started to fill this gap. Festman and colleagues (Festman, Adam, Pratt, & Fischer, 2013a, 2013b) presented a DT target in the path of a manual movement performed first from left to right and then back to the starting point. They found that DT discrimination was best when it appeared in a location far from the hand, but with the hand moving towards it, compared to when it appeared closer to the hand, or the hand was moving away from it. They dubbed this effect the *far-hand effect*.

As we are beginning to see, though there are many similarities between the relationship between attention and saccades and between attention and manual movements, due to some fundamental differences between the types of actions and the body parts involved, there are also some marked distinctions. In the next chapter we will consider in a bit more detail how attention is linked to the body itself, rather than action execution. However, we will first review some of the key points emerging from this chapter.

2.6 Action and Attention – Points of focus

2.6.1 Revisiting the Premotor Theory and the VAM – A more critical look

We started the chapter by looking at two main theoretical frameworks that aim to explain the link between attention and action: the premotor theory (Rizzolatti et al., 1987) and the VAM (Schneider, 1995). Of the two, the premotor theory has been immensely influential, possibly due to being one of the first theories which accounted for the link between actions and attention, in particular in the domain of eye movements. According to the premotor theory the planning of movements and the orienting of attention are one and the same process, and it may be that the apparent simplicity behind it that makes it a more easy theory to disseminate. The VAM on the other hand proposes that attention *precedes* motor planning, and the effects of attentional processing on early visual representations have separate effects along the different visual processing streams. Most of the behavioural data presented so far supports both of these frameworks. Movement curvatures can be explained by the inhibition of planned but not executed actions to a covertly attended location (SfP influencing SfA), while pre-movement attentional allocation can be explained by attention being allocated to a movement target so as to result in better motor programming and execution (SfA influencing SfP). That SfP can influence SfA and vice versa provides support to both frameworks.

Nevertheless, that attention precedes the movement, as proposed by the VAM, appears the more logically sound account, as it is harder to conceptualise how a successful motor program could be programmed to a target *before* attention has both selected it and processed its spatial properties. We have also already seen that attentional effects are observed as early as V1, and before the incoming visual information is processed in premotor areas, which is in line with the mechanisms proposed to underlie the VAM (Kastner et al., 1999; Poort et al., 2012; Roberts et al., 2007; Watanabe et al., 2011).

Another conceptual issue with regards to equating motor programming to attentional orienting is the flexibility of the allocation of VSA that we saw in the previous chapter. Not only can VSA be at times split into multiple non-contiguous locations, but it can be modulated by the shape of an object, change in size and even adopt an annular distribution. Although some of these attentional distributions can be explained easily in terms of action programming e.g. split attention could result from multiple movements being planned in parallel, it is difficult to envision what kind of action would result in a spotlight which changes in size or adopts a ring-like structure.

Further criticism for the premotor theory is provided in a recent review paper by Smith and Schenk (2012). Smith and Schenk argue that the empirical evidence may support a weaker version of the premotor theory, where exogenous attention but not endogenous attention is caused by motor preparation. They point out data from opthalmoplegic patients who have issues in saccade execution who, though exhibiting impairments in exogenous attention, seem to have spared endogenous attention (Henik, Rafal, & Rhodes, 1994; Rafal, Posner, Friedman, Inhoff, & Bernstein, 1988; Sereno, Briand, Amador, & Szapiel, 2006; but see Craighero, Carta, & Fadiga, 2001). This would suggest that motor preparation is not a requirement for spatial orienting of attention. We covered other neuropsychological work which supports this conclusion in section 2.4.2 (p. 48), as Khan et al. (2009) found that successful saccade execution can occur even without presaccadic shifts of attention. Additionally, the patient work by Blangero et al. (2010) found that presaccadic enhancement was displayed by an individual with otherwise impaired covert attention, suggesting that contrary to the claims of the premotor theory, you cannot equate attentional shifts due to movement preparation with all other attentional shifts. One should be careful from inferring too much from the patient data, as the inability to perform a saccade does not necessarily equate with an inability to plan one. However there is also data from non-patients to support a weaker link between motor preparation and shifts of attention. Smith, Schenk, and Rorden (2012) found that exogenous

but not endogenous attention was impaired when attention had to be oriented to a location beyond the oculomotor range of subjects, and thus locations that subjects should not be able to plan or execute movements to.

Smith and Schenk also point out that the neural data also does not support the tenet of the premotor theory that attention results from motor planning, as this would mean that both would share the same neural substrates. We have already seen that although the SC is involved in both, it has differential neural activation patterns involving different neurons depending on the task (Ignashchenkova et al., 2004). The same applies to the frontal eye fields (FEF), a brain structure that has been implied in relaying top-down goals to the SC and other attentional areas (e.g. Khan et al., 2011; Thompson, Biscoe, & Sato, 2005). For example, Thompson et al. (2005) found that in a covert attention task, attentional signals in the FEF could enhance the activity of visually responsive neurons, while inhibiting the activity of saccade-related movement neurons. Furthermore Smith and Schenk point out that areas of the posterior parietal cortex (PPC) involved in VSA do not have a clear role in motor preparation, further dissociating the substrates underlying motor programming and VSA.

Smith and Schenk (2012) instead propose an account where action preparation is only one of different factors that can influence the allocation of attention, while also not being a necessary requirement for it to occur. The attentional target is ultimately selected among the different representations of the visual stimuli, where the strength of each is biased by the stimulus saliency, behavioural goals and motor programming among other factors. This is known as the *biased competition* account of visual attention (BC), originally conceived by Desimone and Duncan (Desimone & Duncan, 1995; Desimone, 1998). This is in some ways reminiscent of the VAM, where attentional allocation can be driven independently by both perceptual (SfP) or action goals (SfA), although according to the VAM SfP would also result in SfA, and thus motor preparation would be a necessary consequence. However as the BC selects only the winner of the competition as the recipient of attention, it is less suited to explain cases in which

attention is allocated to multiple locations, as for example attention being allocated to another target beside the saccade goal (Kowler, Anderson, & Dosher, 1995; Montagnini & Castet, 2007). This is not a limitation the premotor theory has, and in his original conception of the VAM Schneider also allows attention to be allocated beyond a single object token, at least to some degree (Schneider, 1995). In both instances the allocation of attention to a location that was not saccaded to could be accounted by the fact that a saccade was planned to said location, but was not executed. The work by Montagnini and Castet (2007) and Castet et al. (2006) shows that attention builds gradually to a saccade target, so a suppressed saccade target may have had less time for attention to be allocated to it, accounting for impaired performance.

What about the VAM? It is an account that fits well within the Milner and Goodale's framework of two visual streams (1995), and by having motor preparation be a consequence of attention rather than the two being the same, it better accounts for attentional activity in V1 (e.g. Poort et al., 2012; Watanabe et al., 2011), as well as for the separate neural substrates between the two (Ignashchenkova et al., 2004; Thompson et al., 2005). Although the neural substrates may be distinct, the VAM states that they should be sharing attentional resources between them, which is supported by the evidence.

For instance performing both a motor and perceptual task concurrently may impair the performance in one or both (Hesse & Deubel, 2011; Hesse et al., 2012; Moehler & Fiehler, in press; Sandoval Similä & McIntosh, 2015). Although this fits with both the VAM and premotor theory, the fact that attention perceptual performance can be sustained while actions to the same location are suppressed fits more parsimoniously with the former. The VAM posits independent processing streams for action and perception, with separate pragmatic maps in each stream. Within the VAM's framework it would therefore be easier to envision the processing within one stream to be inhibited while the other remains unaffected or is enhanced. This could explain how subjects in the experiment by Sandoval Similä and McIntosh (2015) managed to retain good perceptual performance at a location that was being concurrently

inhibited for motor action. It is harder to envision how this would be the case where perception and action would share neural mechanisms as in the premotor theory. Attentional resources, although independently allocated, also appear to be shared across effectors, albeit this may only be apparent in experiments that are challenging enough (Jonikaitis & Deubel, 2011; Jonikaitis et al., 2010; Khan et al., 2011).

The VAM may at first appear to struggle to explain how defects in oculomotor processing leads to impaired exogenous shifts of attention, which Smith and Schenk (2012) argue supports either a limited version of the premotor theory or BC. Smith et al. (2012) further argue that according to the VAM, attention precedes motor signals so subsequent impaired oculomotor processes should not have an effect. This is a slight misreading of the VAM. Attention does arise in earlier visual areas by enhancing an object token, which then impacts subsequent motor processing, but the creation and enhancement of this object token itself is the result of both bottom-up and top-down factors, including oculomotor processes. In the case of exogenous presentation of stimuli top-down factors are less likely to have time to contribute to the formation of these object tokens, while this is not necessarily the case for the planning of oculomotor responses. For instance, the SC is linked to the retina directly, and thus can receive input at a faster rate than other brain areas (e.g. Jaśkowski & Sobieralska, 2004). Oculomotor signals therefore may play a larger role in forming representations of exogenous attention, and if these are impaired an exogenous object token may fail to be formed. In this respect the VAM is remarkably similar to the BC account.

Where does this leave us? The VAM appears to explain the data as well as, and in some cases better than the premotor theory of attention, not in small part as it does not equate attention and motor preparation as one and the same. Motor preparation may play a larger contribution in the formation of the object token in the case of exogenous attention, which might explain why the impairment in the former results in deficits in the latter more than it influenced endogenous attention (e.g. Smith et al 2012; but see Belopolsky & Theeuwes, 2012). However,

important as motor programming may be in influencing the allocation of VSA, the neural data does not support them being one and the same process, as proposed by Rizzolatti and colleagues (Rizzolatti et al., 1987; Rizzolatti, Riggio, & Sheliga). The data does support perception and action sharing attentional resources as we can see from the effects of SfP on SfA and vice versa. The premotor theory has been very successful in garnering attention both because how it can explain a considerable amount of behavioural data, but also due to its relatively provocative claims that attention and action planning are one of the same. The VAM manages to explain the data and the neural evidence better. Furthermore, it fits within the two visual processing streams framework proposed by Milner and Goodale (1995), which though not without its own controversies and for need of refinement, has been very useful in explaining visual perception (Schenk & McIntosh, 2010).

2.7 Concluding Remarks

As we can see from the literature on presaccadic facilitation and saccadic curvatures, attention and eye movements are undeniably interlinked, but there are different issues with equating saccadic planning with attentional orienting. For one, endogenous attention appears to be more weakly linked with eye movements (e.g. Smith et al., 2012) , but also it is hard to imagine what sort of oculomotor plans would result in an attentional spotlight which changes size and shape in a manner shown in the previous chapter. The VAM is an overall more parsimonious theory, as it allows separate mechanisms in different parts of the brain to interact with preceding attentional allocation independently from one another.

There is a wealth of behavioural data showing that attention tends to precede action execution, whether it be a saccade (e.g. Deubel & Schneider, 1996) or a manual movement (Deubel et al., 1998), albeit this appears to be more tightly linked with the former (Deubel & Schneider, 2003). If presaccadic (and manual movement) perceptual enhancement demonstrates that SfA influences SfP, movement trajectory deviations induced by areas being attended demonstrates also the inverse relationship, supporting that these two share an attentional resource. However

this can be allocated independently to different effectors (Jonikaitis & Deubel, 2011; Khan et al., 2011).

Finally, a manual movement occurs in space and take longer to be execute, and therefore, unlike saccades, it needs to be able to avoid obstacles (Mon-Williams et al., 2001) and update its action plan during execution (Pisella et al., 2000). Recent evidence demonstrates that not only is the end point of the movement attended to, but also the upcoming path of the movement itself (Festman et al., 2013a, 2013b).

Mediated by attention, perception and action have the capacity to influence one another, and many of the effects such as deviations of movement trajectories and perceptual enhancement at the movement target are shared by different effectors. However, just as the actions in question are themselves different from one another, so are some of the details of their relationship with attention. Next we shall explore in more detail how attention and the body itself, rather than the body's actions, are related to one another.

Chapter 3: Attention and the Body

3.1 Introduction

In the first two chapters we reviewed the literature on how attention is allocated in space as well as its relationship with action. Attention is allocated to the movement target, and in the case of manual movements attention is also allocated to potential obstacles along the movement path. This section will focus on the starting point of the manual movement itself and how it influences the allocation of VSA, with an emphasis on hands. This will uncover a gap in the current literature which will motivate the first 5 experiments of the present thesis.

3.2 Paying attention to our bodies

As we saw in the previous chapter, attention is allocated for object avoidance, which not only serves to guide our actions but also keeps our bodies away from harm. We have evolved in a world which interacts with us just as we interact with it, even when we are static. Just as we may reach out to objects in our surroundings, others may reach out to us, at times even aggressively. It is important to be abIe to monitor one's body and keep it out of harm's way. Therefore it is not surprising that attention is also allocated to the area around our bodies, also known as our *peripersonal space*. Just like there are many types of attention, there are several ways in which attention is allocated to our peripersonal space, including somatosensory or proprioceptive attention (for reviews on the multisensory representations near the hand see Holmes and Spence (2004) and Brozzoli, Ehrsson and Farnè (2014)). Here we will focus how the representation of our body influences the allocation of VSA.

Just like the previous two chapters, this one also begins with variations of a Posner task, demonstrating the ubiquity of this paradigm in the study of VSA. Reed, Grubb and Steele (2006) looked at how the allocation of VSA was influenced by arm position, and whether detection of stimuli was facilitated when they appeared near the hand. In their first experiment,

Reed and colleagues had subjects carry out a detection task in which participants had to respond as quickly and accurately as possible when a target appeared within one of two boxes on the screen, while maintaining fixation. The location at which the target was going to appear was validly cued 70% of the time by the darkening of one of the squares. The novel aspect of the work by Reed et al. was that they had participants extend either their left or right arm next to the target box on the respective side. They found faster detection of the target when it appeared close to the hand, as one would expect if VSA was allocated also to one's peripersonal space. It is possible that the presence of the hand acted merely as a visual anchor, attracting attention to that area of space rather than being due to the presence of the hand itself. However Experiment 2 had the same procedure, but included a control condition in which neither arm was extended, but a wooden block of roughly the same shape and size was placed next to one of the targets, in the same position as the extended arm would have been. This second experiment replicated the findings of their first one, while failing to fail any facilitation effects for the wooden block. Their third experiment investigated instead how important it was to have the hand visible for facilitation of peripersonal space to occur, by having participants put their hands in the same location, but hidden inside a black box. Once again, subjects performed better when the target appeared on the side containing the hand, but this effect was significantly less pronounced than when subjects had both proprioceptive and visual input. This suggests that monitoring one's own peripersonal space is better when it is visible, but proprioceptive contributions alone also play a role. A fourth experiment investigated whether visual information alone without matching proprioceptive information would also result in enhancement of VSA. Subjects put on a yellow rubber glove, and a rubber hand was made to look their gloved hand by also putting a rubber glove on it. The gloved rubber hand was placed near one of the targets in a manner similar to the wooden block in Experiment 2, while participants placed their real hand on their lap. Just as Experiment 3 found less attentional allocation near the hand when it was felt but not seen, the same effect was found in Experiment 4 where the hand was seen but not felt. Although vision alone was enough to induce an effect,

attentional allocation is strongest when it receives matching input from both sensory modalities. There is some evidence suggesting that of the two sensory modalities vision may be the predominant one (e.g. Graziano, 1999; Welch & Warren, 1986), although this relationship has been found to be reversed in the spatial dimension of depth (van Beers, Wolpert, & Haggard, 2002). In a final experiment, Reed and colleagues investigated the extent of the space around the limb which receives facilitation. They had two conditions: either the hand was close to the possible target position on the respective side as in the previous experiments, or the hand was a further away (11cm) from the target and on the edge of the screen. When they compared RTs for validly cued targets, they found that participants responded the fastest to the target when the hand was placed next to it, followed by when the hand being further away but still on the same hemifield, and they were slowest when the hand was on the other side of the screen. This suggests a gradual decrease of attentional enhancement as the distance from the body increases.

Reed et al. (2006) propose that their findings reflect the activity of bimodal neurons which respond both to visual and tactile stimuli in the area of the pertinent body part, as well as to visual stimuli occurring around it (Graziano & Gross, 1993, 1995; Làdavas, 2002). Làdavas (2002) argues that the role of these bimodal neurons is to fire for stimuli that are within potential reach of the body part, and indeed they have been shown to have a gradual attenuated response as the distance from the body increases (Làdavas, Pellegrino, Farnè, & Zeloni, 1998). Graziano and Gross propose that this enhancement could stretch as far as 20cm around the body (1995), which is consistent with the findings obtained by Reed et al. (2006).

Dufour and Touzalin (2008) obtained broadly similar results as Reed and colleagues in a paradigm where participants had to detect or discriminate the colour of an LED placed either near or far from the participants' hands. The only discrepancy between their results and those of Reed et al. (2006) is that they failed to find evidence of proprioceptive contributions without vision of the hand when they conducted the experiment in the dark. However this may have

been due to their smaller sample size (8 vs 27 subjects used by Reed et al.), and so might have lacked statistical power to detect any subtle contributions provided by proprioception. Whatever the role of proprioception, the attentional enhancement around one's body can also be extended to encompass tools one might be using (Reed, Betz, Garza, & Roberts Jr., 2010), and its focus can be shifted from one hand over another depending on task requirements (Garza, Strom, Wright, Roberts, & Reed, 2013). Such flexibility should come as no surprise after the literature covered in the first two sections. For a brief review see Brockmole, Davoli, Abrams and Witt (2013).

However, data from the clinical literature is less clear. In 2004 Schendel and Robertson reported of a patient (WM) who had lost vision in his left hemifield due to damage to his right visual cortex following a stroke. They found that extending the arm into the blind hemifield significantly improved detection rates for stimuli presented on that side, which, like Reed et al. (2006), they attribute to activity of bimodal neurons. However, it is important not to generalise too much from these results, as Smith, Lane and Schenk (2008) failed to replicate these findings in 5 other patients.

3.3 The body catches attention?

So far these experiments have suggested attentional enhancement near the hands, but what does this *peripersonal enhancement* mean for orienting attention to the rest of the visual environment? Considering that people have a limited attentional capacity, one would expect that paying attention to the space around one's body would result in a cost in orienting attention elsewhere. This is indeed what Abrams, Davoli, Du, Knapp and Paull find (2008). In their first experiment they had participants place both their hands either close or far away from the screen, and carry out a visual search task with either 4 or 8 items on display. As one would expect, people performed the visual search task faster when there were fewer items on display. More interestingly though, the increase in search time when increasing the number of items was larger for the trials in which the hands were close to the screen than when they were far

away from it. This suggests that the presence of the hands somehow slowed down the attentional shifts. It bears noting though that there was no difference in the baseline search times between conditions with the four-item display, suggesting that this slow-down of attention may be quite small and only become apparent in longer serial searches. A second experiment looked at how the phenomenon called *inhibition of return* (IOR) was affected. IOR is the phenomenon in which after a location has been attended and the location is perceptually enhanced, a subsequent response to that location is then inhibited (Posner & Cohen, 1984). Abrams and colleagues' second experiment found a weaker IOR-effect when the hands were close to the screen, while the cueing effect at short stimulus intervals was unaffected. IOR is believed to have the functional role of helping one scan the environment by ensuring efficient disengagement from a previously attended location (Klein, 2000). The second experiment therefore suggests that the findings of the first experiment may be explained by slower disengagement from each of the stimuli on screen when the hands are nearby. When stimuli are presented close to the hands, the attentional system may want to ensure a more in-depth processing of them before moving on to the next target, in case they are a potential source of danger or are otherwise pertinent to one's behavioural goals.

In order to strengthen the interpretation that attentional disengagement was at the root of their findings in their first two experiments Abrams and colleagues carried out a final experiment which investigated a phenomenon that is believed to demonstrate attentional disengagement in action. When two stimuli are briefly and serially presented close in time to one another at the same location, the second one is often masked by the first one and is not detected, in a phenomenon known as the *attentional blink* (AB; Raymond, Shapiro, & Arnell, 1992; Shapiro, Raymond, & Arnell, 1994). It is believed that this effect shows that processing of the first stimulus needs to be completed before a second one can be processed, and thus reflects the rate at which attention is disengaged from the first stimulus. Therefore this is an ideal paradigm for Abrams et al. to use to put their interpretation to the test. If the proximity of hands slows

attentional disengagement, then the presence of the hands during an attentional blink-task should lengthen the duration of the AB. This prediction was indeed confirmed. Detection of the first target itself was not influenced by the proximity of the hands, but when the second target was presented on the following frame (80ms), discrimination accuracy of the second target when the hands were close was down significantly to 65% compared to 70% when the hands were further away. The relatively small difference between the accuracies bears noting.

Similar results of hand proximity reducing the effect of masks (Goodhew, Gozli, Ferber, & Pratt 2013) and the distracting effects of flanking stimuli (Davoli & Brockmole, 2012) strengthen the claims made by Abrams et al. (2008) regarding what underlies this enhancement. VSA, once allocated to stimuli in our peripersonal space, is anchored there so as to allow them to be processed more thoroughly, at the expense of attending to stimuli elsewhere. However, as we can see from the results of Abrams et al. (2008) the effects can be fairly modest in magnitude, which is fortuitous as one would not want one's attention to be solely focused to one's body and its close surroundings. Apart from the disadvantages of appearing too narcissistic to others, one's wider environment remains a worthy recipient of one's attention.

3.4 An unanswered question – Attention and the starting point of a movement

One of the roles of attention is to ensure better processing of information that would result in better action planning and execution. We have seen that attention gets allocated to the end point of a pointing movement (e.g. Deubel et al., 1998), as well as along its trajectory (Adam, Bovend'Eerdt, van Dooren, Fischer, & Pratt, 2012; Festman et al., 2013a, 2013b), and we just saw that even stimuli appearing near static hands also receive enhanced processing (Abrams et al, 2008; Reed et al., 2006). However allocation of VSA to the actual *starting point* of a manual action has been neglected. In order to execute a successful action, for example

pointing, we know that attention is allocated to the target so as to better process its properties. However, in order to compute the trajectory of the movement, not only do we need to know where the target is in space, but also where it is in relation to the hand that is about to act. The question then arises, is attention allocated not only to the movement end point, but also to the moving start point so as to have better information with which to plan the whole movement?

We have separate representations of different effectors in our brain (e.g. Haggard, Newman, Blundell, & Andrew, 2000), but more crucially, there is evidence from fMRI indicating that when computing a movement vector, both the effector and the movement target are processed (Buneo & Andersen, 2012; Buneo, Jarvis, Batista, & Andersen, 2002; Mascaro, Battaglia-Mayer, Nasi, Amit, & Caminiti, 2003; Medendorp, Goltz, Crawford, & Vilis, 2005). However, this still does not address the question as to whether any attention is allocated to the location of the physical effector itself. Some recent ERP studies have attempted to address the question. Press, Gherri, Heyes, and Eimer (2009) investigated the effects of preparing and executing an action at a specific location on attention to that location. Subjects were shown two hands on either side of the screen, and had to either tap or lift a finger with a previously instructed hand once one of the hands on the screen tapped or lifted a finger. A left hand was shown on the left hand of the screen, and a right hand was shown on the right hand of the screen. This meant that the action shown on screen could be either congruent or incongruent with the action to be executed, as well as spatially congruent or incongruent with the location of the action. Early visual ERP components were enhanced at the spatially congruent conditions, while no such early modulations were visible for action congruency, suggesting that attention is drawn to the action location. Similar results were obtained in a second experiment where people responded on some trials verbally rather than by tapping, with the verbal responses consisting on saying "Up" or "Down" depending on the central cue. That these effects can be seen also for verbal responses suggests that these effects are not effector specific but influence also other mental representations.

In a related experiment Gherri and Eimer (2010) found that preparing a finger lift disrupted the allocation of attention to the contralateral side to the action, as measured by ERP signals. This was the case even though on each trial participants had to ultimately either execute the instructed action or carry out a detection task. The action consisted of a simple finger-lift, while the discrimination task consisted verbally reporting the appearance of a target LED on the instructed side, close to the hand. Taken together these experiments point to the conclusion that action preparation can both facilitate attentional performance at a congruent location, and also disrupt the allocation of attention to an incongruent location.

Although the work by Eimer and Gherri (2010) demonstrates that *action preparation* influences the allocation of VSA, it does not address a related question as to which components of the action preparation play a role. More specifically, is attention being allocated only to the target of the action, or also to the effector itself? When one considers how attention is allocated even to a static arm (e.g. Reed et al., 2006), action preparation drawing VSA to the space occupied by the effector is an intriguing possibility. Both Eimer and Gherri (2010) and Press et al. (2009) had participants execute actions which consisted of either the tapping or the lowering or lifting of a finger, and as such the target of the action and the location of the effector are one and the same. Thus these experiments are ill suited to address this question.

Before proceeding to suggest how this question could be answered, there is one detail worth elaborating on. That is, whether the question pertains to the relationship between VSA and the acting hand, or VSA and the *space* the hand occupies. It may initially seem that there is no meaningful distinction between these two interpretations, as the space the hand occupies and the hand itself are intrinsically linked. The former is naturally determined by the location of the latter. However other factors beyond vision, such as proprioception and tactile feedback, provide a role in a comprehensive representation of the hand (Holmes & Spence, 2004; Reed et al., 2006). In order to fully understand the links between VSA (or attention in general) and the hand requires a multisensory approach, and is beyond the scope of this thesis. Nevertheless

investigating whether VSA is allocated to the starting location of a movement is a natural place to start unravelling this issue.

A way of doing so is to have participants execute a pointing task similar to those cited in the previous chapter (e.g. Deubel et al., 1998; Jonikaitis & Deubel 2010). These involved participants pointing at indicated targets and assessing how well they could discriminate a DT when it appeared at the target location compared to when the DT appeared at other locations. This allows one to separate the effector starting point from the action-target, and to probe attentional allocation at both locations. Ensuring that participants choose the effector on each trials can also be achieved quite simply by having the pointing hand vary in between trials. This is important in order to ensure that the effector is selected on each trial, as otherwise attention may not be allocated to a location that is known in advance, as we have seen occur with delayed manual movements (Deubel & Schneider, 2003). This is the approach taken by the experiments outlined in the present thesis.

3.5 Brief Experimental Outline

The first 5 experiments of this thesis utilised variations of the paradigm described above to better answer the question whether spatial attention is not only allocated to the target of the movement, but to its start point as well. The results indicated that this may occur under the correct circumstances, but this effect is less robust than attentional allocation to the movement target, or even attention allocated to one's peripersonal space. There are two reasons that may explain this pattern of results. The first is that it is difficult to split attention to multiple locations no matter the kind of task, so the experiment must be calibrated to an appropriate difficulty setting. A second explanation is that allocating attention to the movement effector as well as to the movement target is either more difficult or less essential for movement planning compared to attending to multiple movement targets. The final experiments are attempts to replicate the results obtained by Baldauf et al. (2006), who had found that attention is allocated in parallel to all the targets of multistep pointing movements at little or no cost. If

these results were replicated, it would have been a clear indication that the allocating to multiple locations is easier for multiple targets than it is for a single target and effector. However the replication attempts proved ultimately unsuccessful, indicating that VSA is not easily split to multiple locations, if it is at all, and caution should be taken regarding the generalisability of some results in the literature. The implications and recommendations for future work are discussed in more detail in the final chapter.

Chapter 4: Does it matter where we come from?: Allocation of attention to the movement start point

4.1 Experiment 1: Exploring the role of movement predictability on perceptual enhancement

4.1.1 Introduction

We have seen in Chapter 2 how attention appears to be tightly linked to action guidance, with the targets of both saccades (e.g. Deubel & Schneider, 1996) and manual movements (e.g. Deubel et al., 1998) receiving attentional enhancement. In the case of manual movements, there is also recent evidence showing attentional enhancement for stimuli presented along the trajectory of manual movements (Festman et al., 2013a, 2013b). Thus we have evidence that for manual movements attention is allocated both to the movement target and along the movement path, but whether the starting point of the movement itself is attended to is still an open question.

As we saw in the previous chapter, there are several recent studies which have shown perceptual enhancement at the location of a static hand at the expense of processing stimuli presented elsewhere (e.g. Reed et al., 2006; Abrams et al., 2008), thus showing that the hand does not need to be moving in order for attention to be allocated to it. More crucially though, the preparation of a finger movement has been shown to enhance attentional allocation to stimuli to that visual hemifield (Press et al., 2007), while also disrupting allocation of attention at the contralateral hemifield (Gherri & Eimer, 2010). Considering these latter findings, it would be surprising if attention was allocated to the target, along the movement path, and even to a static hand, but stopped short of additionally enhancing an effector's starting point when

a movement was imminent. However, attentional allocation to the origin of the movement has not been empirically or directly tested.

Previous experiments studying allocation of attention to manual movement targets have had multiple possible movement targets, often in a circular array, and measured allocation of attention by briefly showing probes at different potential target locations and recording discrimination accuracies (e.g. Jonikaitis & Deubel, 2010; Baldauf et al., 2006). In such paradigms, the moving hand has tended to be at the centre of the array, and participants would point at the indicated target at the appearance of a central cue, often an arrow. Crucially, participants would always respond with the same hand, and attention at the starting location was never measured. Our experiments departed from this format. Hands were positioned in coincidence with potential probe locations, and participants had to point with either hand. For the first four experiments we had two potential target locations and two start locations (one per hand). This was done in order to maintain a balance between the number of potential targets and potential effectors, thus attempting to make the selection process between the two equally difficult. Although it is easy to increase the number of targets to choose from, it is not equally easy to increase the number of effectors, certainly not hands, to a number above two. Attentional allocation itself was measured via a two-alternative forced choice task (2AFC), where subjects had to report which of two possible DTs had been briefly presented. Discrimination performance was taken as an indication of the amount of attentional resources at a location. As in previous work, subjects were told to prioritise the pointing task over the perceptual task (e.g. Baldauf & Deubel, 2008; Baldauf et al., 2006). In order to limit the trial numbers, the DT always appeared either at the movement's starting or end position.

Beyond assessing attentional allocation at a movement's starting point and comparing it with performance at the attentional target, Experiment 1 attempted to address another question. As we saw in the first chapter (p. 12), Posner and colleagues (1980) found that in a Posner task, when they kept the location a stimulus was going to appear constant there was no attentional

benefit at that location. This is consistent with the finding that manual movements can be planned in advance and be executed from memory without producing mandatory shifts of attention pre-execution (Deubel & Schneider, 2003). In other words, if a location is predictable, no, or at the very least fewer, attentional resources are allocated to it. We decided to investigate the role of the predictability of a movement-relevant location further, and see how attention at the hands may be influenced by it. We had three different block types: in the first two either the movement target or the effector (i.e. the moving hand) was kept constant, while in the third one both locations could change between trials. In accordance to the findings of Posner et al. (1980), we expected that locations that changed on a trial-by-trial basis and were not known in advance to receive additional attentional enhancement, compared to constant locations. For example we expected to find better perceptual performance at the movement's start locations on blocks where this was not known in advance, whereas perceptual performance would be better at the target location on blocks where the movement target was known in advance. In other words, more attention would be allocated to a location when it was not known in advance than when it was, and this would apply both to the movement target and the movement's start point.

In our first experiment participants had to point to one of two possible movement targets, with one of their two hands. The hands in turn were placed on two other points on the screen, where the DT could also appear. We used arrows to indicate both the target and the moving hand. Although arrows have often been used to indicate movement targets, some work has suggested that arrows may be such familiar cues from everyday life as to elicit reflexive shifts of attention (Brignani, Guzzon, Marzi, & Miniussi, 2009; Guzzon, Brignani, Miniussi, & Marzi, 2010; Ristic & Kingstone, 2006; but see Baldauf et al., 2006). It is possible that the use of arrows may therefore mask some of attentional effects that we are interested in, but using two arrows would mean that any effect they would elicit should be evenly shared between the different block types and movement locations. In other words, if the pattern of perceptual enhancement

at the movement target was due to it having been indicated by an arrow, then we would have expected similar perceptual performance at the movement's start point. Thus any differences we would manage to observe between blocks and locations would be even more compelling.

Consistent with previous literature, Experiment 1 found attention to be preferentially allocated to the movement target. However contrary to our expectations, we found no effect of block type on the way attention was allocated to either a movement's starting- or end-point, and our prediction that knowing in advance a different component of the movement could alter the way attention was allocated was not supported. This suggests that the movement target is prioritised by VSA over the movement's start point.

4.1.2 Method

4.1.2.1 Participants

Sixteen participants (9 females, 7 males, mean age = 22.4 years SD = 3.77) took part in Experiment 1. They had normal or corrected-to-normal vision (though no glasses as this interfered with the eye tracking) and were right-handed by self-report. All were reimbursed £6 for their time. This study was approved by the Psychology Research Ethics Committee, University of Edinburgh.

4.1.2.2 General Set-up

For the general set-up see Figure 4.1 (p. 87). Participants were seated in a darkened room, with their head placed on the chinrest of an Eyelink 1000 Tower Mount (SR Research, Osgoode, Canada), a video-based eye-tracking system. The eye-tracker was used to ensure participants maintained fixation through the duration of each trial. The experiment was designed and implemented using SR Research Experiment Builder 1.1.2. Stimuli were presented on a 21" monitor (400 x 300 mm, 1024 x 768 pixels resolution, 100 Hz refresh rate) and projected onto an inclined working surface (12°) using an inclined mirror (6°). This arrangement allowed the stimuli to appear to be presented on the working surface, while simultaneously keeping the

hands out of view. This was done so as to avoid any visual transients from the hands, which might have induced exogenous shifts of attention. Subjects maintained fixation for the duration of the trial on a white 'X' (0.85° x 0.85°), located 3.1° below the centre of the screen. The movement starting points and targets were located at the corners of an imaginary square centered around fixation (8.1° x 8.1°), and were represented by digital 8s (1.3° x 2.0°). Half of the participants had their left hand in spatial coincidence with the bottom-left '8', and other half had their right hand in spatial coincidence with the top-right '8'. The movement targets were the other two 8s. The other half of the participants placed their left and right hands 'on' the top-left and bottom-right 8s respectively. These four locations were indicated on the wooden working surface by small coins (50 rappen, diameter: 1.82 cm). This provided tactile feedback to subjects indicating the starting and end positions of the movements. The fixation point was projected 304mm up the working surface, while the lower and upper stimuli were 226mm and 383mm up the working surface. The moving hand and movement target were indicated by two arrows (1.25° each) which briefly (200ms) replaced the fixation cross. All stimuli where white (102 cd/m^2) presented on a black background (1.1 cd/m^2).

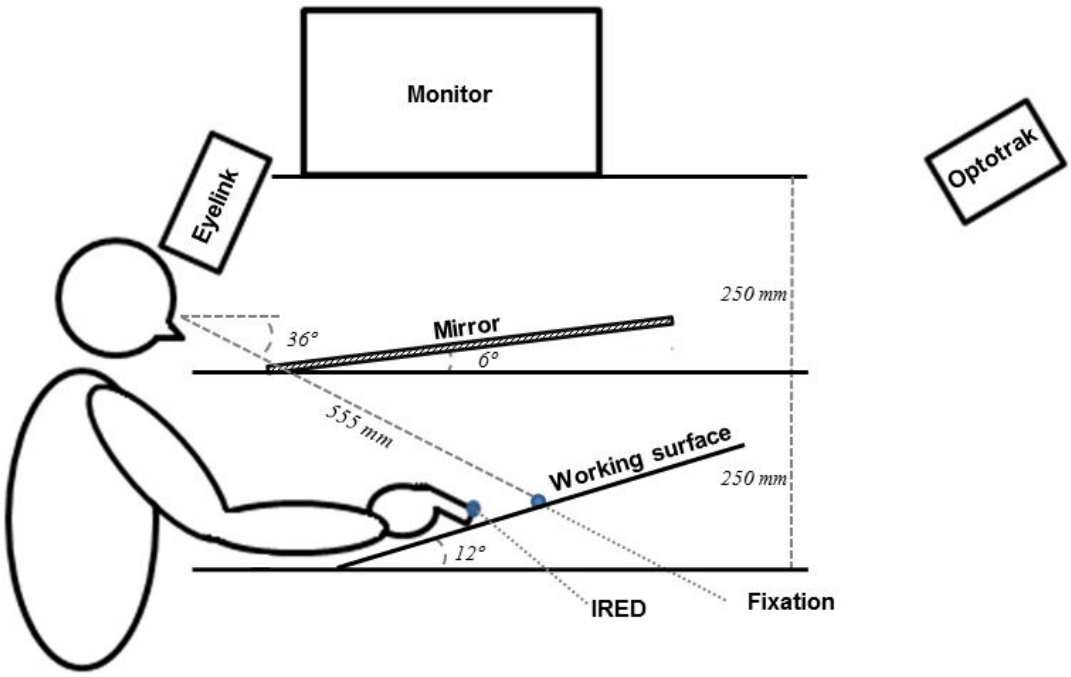

Figure 4.1. Schematic diagram of the experimental set-up (not to scale, chinrest and one arm not shown). Stimuli were presented on a monitor and optically projected via a mirror to an inclined working surface in front of the participant. Solid lines indicate critical components of the apparatus, dashed lines are included to indicate measurements and dotted lines to assign labels. Figure adapted from Sandoval Similä and McIntosh (2015).

Eye movements were sampled at a rate of 1000 Hz, and an eye movement was considered to have occurred if a saccade was detected outside an ellipse of area of 40 x 40 pixels around fixation (0.81°). A three-point horizontal calibration was carried out at the start of the experiment and repeated as necessary throughout the experiment. This was rare, and usually limited to the start of each block. Drift correction, ensuring correct starting fixation, was carried out before the start of each trial. Manual movements were recorded utilising the Optotrak Certus 3020 system (Northern Digital Inc., Waterloo, Canada), which sampled the 3D spatial location of two infrared-emitting diodes (IREDs), at a frequency of 100 Hz. An IRED was attached to the nail of each index finger of the participants.

4.1.2.3 Procedure

Trial sequence: The trial sequence can be seen in Figure 4.2 (p. 89). Following a drift correction, subjects were presented with an initial screen consisting of the fixation point

surrounded by four digital 8s. After 700ms, the initial screen was replaced by the Cue-Screen, in which the fixation cross was replaced by two arrows indicating the movements' starting and end points (Figure 4.3, p. 90). One of the two arrows always pointed at the location of one of the two hands, while the other arrow pointed at one of the two remaining locations which did not contain one of the participant's hands. The first arrow thus indicated to the participant which hand was to perform the pointing movement, and the other arrow indicated where the movement was to be directed. They were presented for 200ms, and their onset was accompanied by an audio cue ('BEEP'). The initial screen was then presented again (60ms), followed by the probe screen (400ms). The probe screen had one of the digital 8s, either the movement's starting or end point, replaced by a digital two or a five. The other 8s changed randomly into vertically mirrored digital 6s or 9s. Numeric targets were used rather than an E or a digital 3 (e.g. Deubel et al., 1998) in case the use of numeric distractors would bias the participants' identification of the stimuli causing them to over-report the presence of the digital 3. These targets and distractors were used until Experiment 5, after which we used stimuli akin to previous paradigms (e.g. Baldauf et al., 2006; Deubel et al., 1998). The cue screen was then followed by the initial screen for 1600ms, followed by the verbal response screen consisting of the text "2 or a 5?", during which subjects would verbally respond which of the two DTs had been presented. Subjects were told to guess if uncertain. The participants' responses were keyed in by the experimenter. Subjects would then return their hand to the starting position.

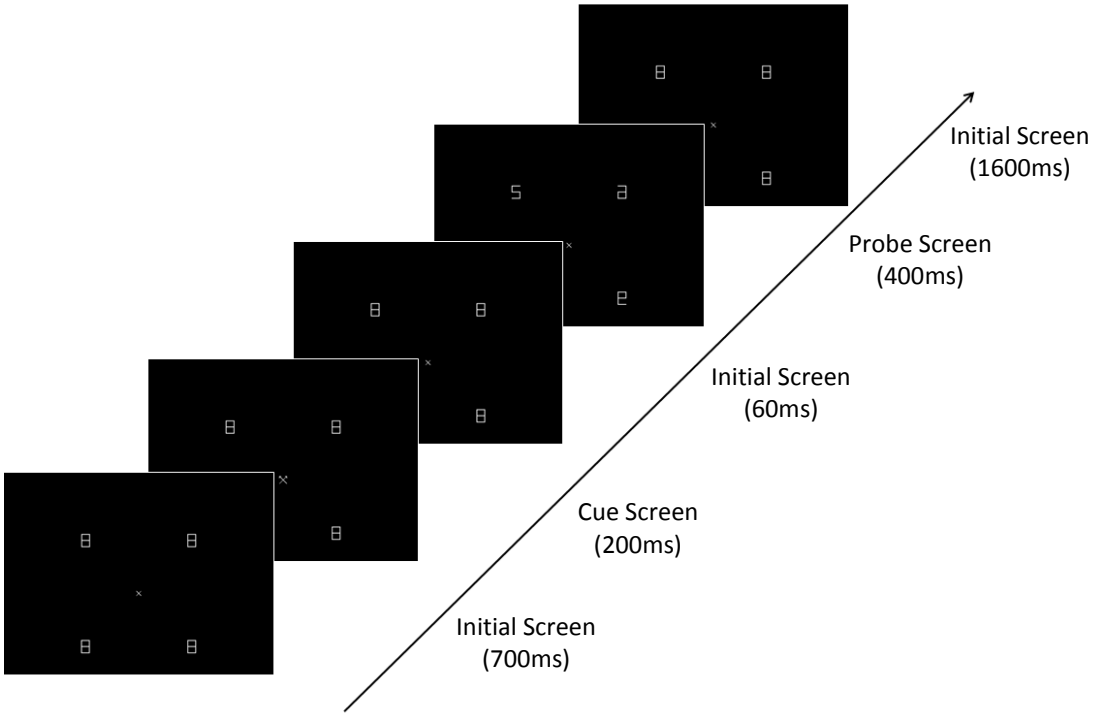

Figure 4.2. Trial sequence for Experiment 1. Following drift correction, the initial screen is shown for 700ms, after which the fixation cross was replaced by two arrows for 200ms, accompanied by a beep. One arrow indicated which hand subjects were to move on that trial, as well as which of the two targets they had to point at. This was replaced by the initial screen for another 60ms, after which the probe screen was presented (400ms). This contained the DT, which was either a digital 5 or a 2, and replaced the digital 8 either at the movement's start or end location. The other figure 8s were replaced by distractors (vertically reflected digital 6s or 9s). This was then followed again by the initial screen (1600ms), after which subjects were presented with a response screen (not shown), and they had to verbally report which DT was reported. Subjects were told to maintain fixation until the response screen.

There were three different block types: either the movement target or the moving hand was known in advance (*hand-* or t*arget-unknown* blocks respectively), or they both varied (*mixed* block). There were two types of target-unknown blocks, as either the participants used their left or right hand throughout a block, and similarly two types of hand-unknown blocks, where subjects had to point to the same one of the two potential targets throughout the block. Participants began the experimental session by carrying out a 20-trial mixed block for practice. This was followed by two blocks of each type, utilising an AABBCC pattern, resulting in 6 experimental blocks. The order of the type of block was counterbalanced between participants. The first block of each hand-unknown section always began with participants reaching for the bottom target, and the first block in the target-unknown section started with participants using their right hand. Each experimental block was preceded by 5-trial practice block, in order to

let participants get accustomed to the different instructions. An experimental block consisted of 32 randomly shuffled trials, with the DT appearing at the movement's start location on half of the trials, and at the target location on the remaining 16. Trials where subjects broke fixation before the verbal response screen were reshuffled into the sequence. In such cases the trial was interrupted with the appearance of a black screen for 500ms accompanied by an error sound. There were a total of 192 trials per participant, or 64 per block type. The DT appeared on at the target on 50% of the trials, and at the movement's starting location on the other 50%. In the target-unknown blocks, both targets were equiprobable, while the moving hand was kept constant throughout the block. In contrast, in the hand-unknown blocks the target was kept constant, and the participant moved either hand on half of the trials. Finally, in the mixed blocks both the moving hands and the movement targets were equally likely, and occurred on half of the trials.

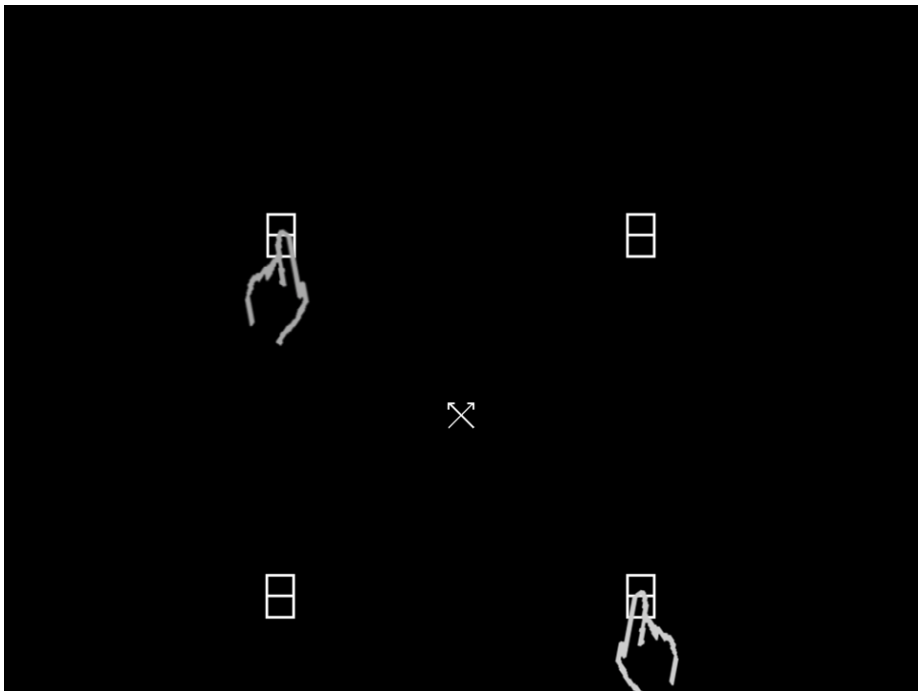

Figure 4.3. Example of a cue screen. One of the arrows indicated which of the hands is to do the movement, while the other determined the movement target (i.e. the hand which was pointed by an arrow was designated as the moving hand, and the pointed to location without a hand was designated as the movement target). In the above example the left hand on the top left had to move to the top right target. N.B. The hands were below the mirror, and were not visible to the participants.

4.1.2.4 Data Processing

Due to misinterpreting the task and cues and consistently moving the incorrect hand in their mixed blocks, one participant was removed from the analysis. For the remaining participants, trials with incomplete kinematic data due to occlusion of the IREDs (12.4%), and trials in which subjects either moved the wrong hand or reached for the incorrect target (7.0%) were removed from the analyses. Subjects were considered to have reached for the wrong target if they landed closer to the incorrect target than to the cued target, or if their trajectory initially appeared to be heading for the incorrect movement target. Finally, the mean RT was obtained for each participant, and trials two standard deviations above or below this mean were also removed (3.6%).

The critical DV was the participants' accuracy in discriminating the DT depending on the block type (3 levels: Hand-unknown, Target unknown and Mixed blocks) and where the DT was presented (2 levels: movement start point, movement end point). In order to retain greater levels of statistical power, data for the left and right hands was collapsed together, except for analyses which looked specifically at hand differences. The same applied to the data for the different target locations and manual setups. The mean DT-discrimination accuracies for the different conditions were then obtained separately for when the DT was a 2 or a 5. This was done to counter any biases participants may have had for saying either number if one type of trial was overrepresented following data filtering. For inferential statistics, as our perceptual data consisted of proportions, these values were arcsine transformed in order to normalise the distribution, before being averaged together. However, for clearer visualisation, the descriptive statistics were run on the averages of the non-transformed data.

Although previous work has managed to achieve good perceptual performance with lower DT presentation times (e.g. Deubel et al., 1998), prior piloting found that we required longer presentation times for the DT discrimination to be feasible (see also Van der Stigchel &

Theeuwes, 2005). This meant that in the majority of our trials (84.4%) the DT was still present at movement onset, thus making it hard to make claims that these results reflect solely pre-movement attentional allocation. Nevertheless, the probe was present on average for 240ms before movement onset (SD = 159ms), over half the DTs presentation time, therefore pre-movement shifts of attention were in all likelihood also being assessed. The first experiment can therefore be seen to address a more general question of whether attentional allocation in general, not necessarily just pre-movement shifts, would be influenced by advance knowledge of the upcoming movement.

The movement data were processed with custom-made software in the LabVIEW environment. The raw kinematic data was filtered through a dual pass Butterworth low pass filter with a cut-off of 20Hz. Movement onset was deemed to have taken place when the movement speed exceeded 50mm/s and sustained for above 10 frames, and the movement offset was marked by the frame after which the speed fell below this value (e.g. McIntosh et al., 2010). RT was taken as the time between the onset of the cue screen and movement onset. Movement duration (*MD*) was taken as the time between movement onsets and offset. Movement accuracies were assessed by the distance (in mm) between each movement's end-point and previously calibrated target locations. For the first 4 Experiments the calibrated locations had been obtained once per physical set-up by placing the markers on the coins, and used across the different participants. However from Experiment 5 onwards the calibration was done separately for each participant at the start of each experimental session, with the markers attached to the participants' index fingers. The accuracy of the movements was assessed via their landing accuracy (LA), which was the distance between a movement's landing position and the calibrated location of the movement target. In order for a movement to have been judged as having gone to the correct target, it had to land closer to the cued target than any other one. The overall even distribution of the landing accuracies seen in Figure 4.4 (p. 93) suggests that this was an accurate measure of movement accuracy.

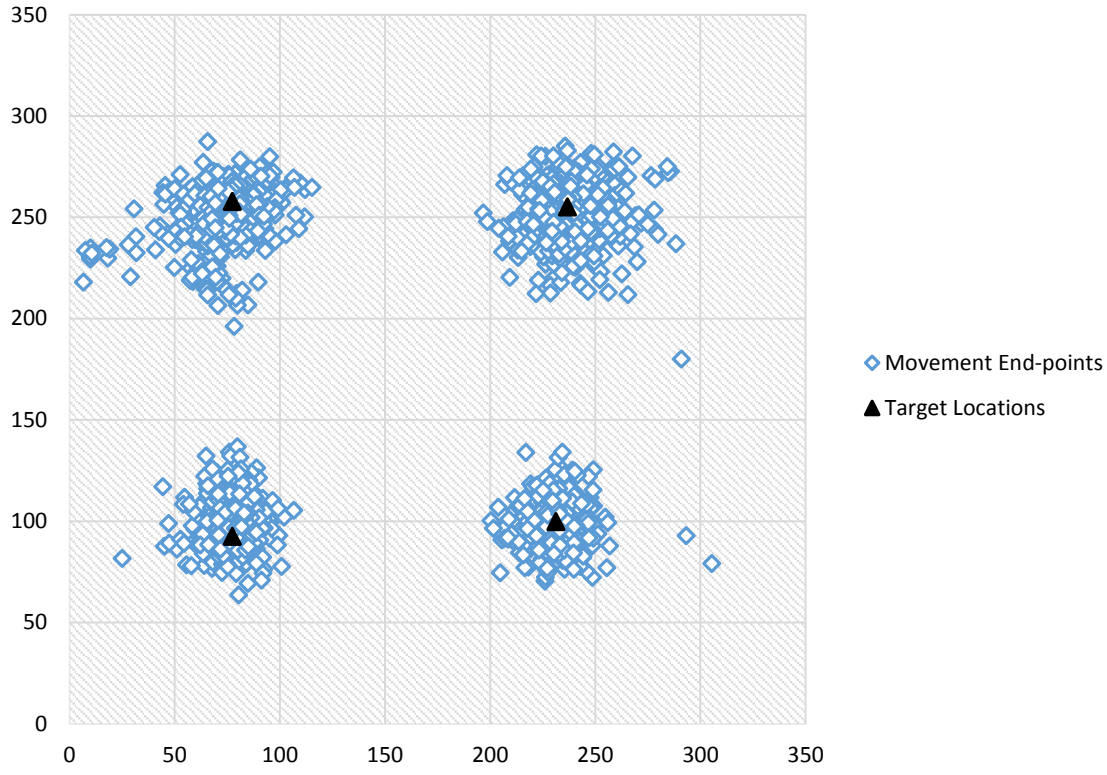

Figure 4.4. Overall landing accuracies and the calibrated target locations. Both axes are in mm. NB. Each participant had to both point at the bottom-left and top-right targets, or at the top-left and bottom-right targets, depending on their assigned manual set-up.

4.1.3 Results

4.1.3.1 Perceptual Performance

What we were most interested in was how the different conditions influenced the way VSA was allocated across the visual landscape. The DT could appear at the movement target location as in previous studies (e.g. Deubel et al., 1998) or at the movement's starting location, and how much and which feature of the upcoming movement was known in advance was altered between blocks. The pattern of the results can be seen in Figure 4.5 (p. 94).

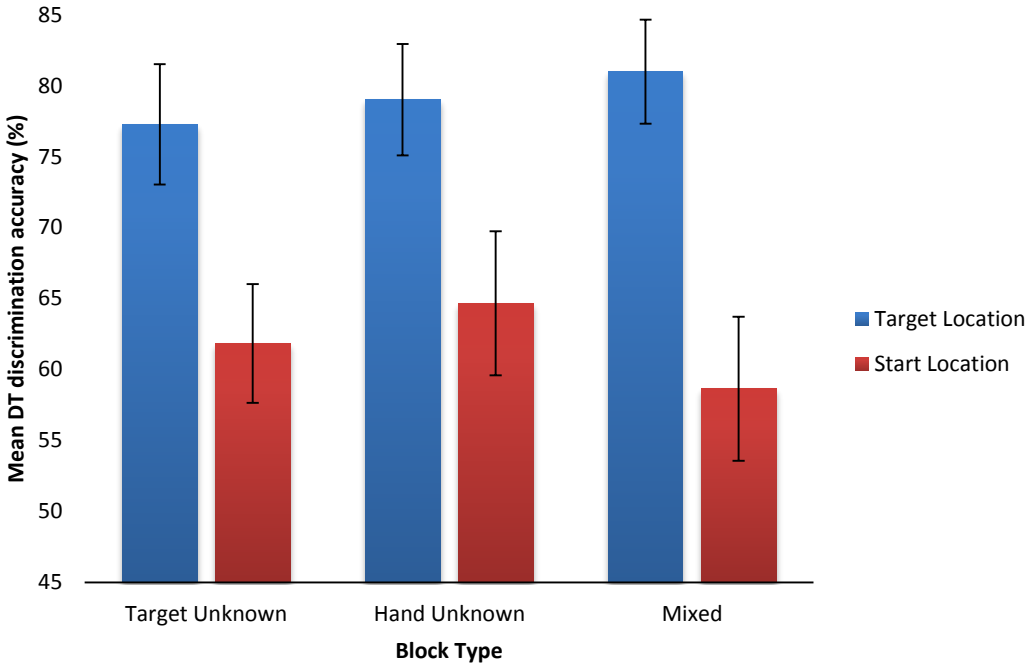

Figure 4.5. Mean DT detection accuracies (%) for at the movement's end and start locations for the different block types. The error bars represent standard errors.

We conducted a 3 (block type: target unknown, hand unknown or mixed block) X 2 (location: hand vs target location) repeated measures ANOVA. There was a main effect of the relative probe location, with perceptual performance at the movement's target location being better than at the start location ($F(1, 14) = 10.81$, $p = 0.005$, $\eta_p^2 = 0.44$). There was no main effect of block type on the pattern of attentional allocation ($F(1,14) = 0.29$, $p = 0.75$, $\eta_p^2 = 0.02$). However, more surprisingly, the interaction between block type and probe location was not significant: subjects performed better when the DT appeared at the target location regardless of block type ($F(2,28) = 1.62$, $p = 0.22$, $\eta_p^2 = 0.10$).

Conducting one-sampled t-tests on the discrimination means found that only performance for target-unknown blocks (M = 61.8%, SD = 16.7) was respectively significantly above chance at the movement's starting location ($t(14) = 2.18$, $p = 0.047$, $d = 0.56$). Discrimination accuracy at the starting location at the hand-unknown blocks (M = 64.7%, SD = 20.3) or in the mixed blocks (M = 58.7%, SD = 20.3) were not significantly above chance ($t(14) = 2.07$, $p = 0.057$, $d = 0.53$) and $t(14) = 1.27$, $p = 0.23$, $d = 0.33$ respectively), but the results were in the expected

direction. An important consideration when interpreting these results is that in order to limit the trial numbers, the DT always appeared at a *movement relevant* location i.e. at the movement's start or end points. Therefore we cannot assess whether attentional performance at the movement start point was better than in the rest of the visual landscape. This is looked at in Experiment 2.

4.1.3.2 Movement Performance

We saw in the above section that the discrimination of the DT was best at the target location, regardless of block. Did the DT location or the block type have any significant effect on the movement performance? A summary of the different movement parameters for the different block types divided by the location in which the DT appeared can be seen in Table 4.1.

Table 4.1. Means and SDs of the different movement variables (reaction time (RT), movement duration (MD) and landing accuracy (LA). These have been broken down by block type and location where the DT appeared: i.e. whether the participants did not know the target, movement hand or neither in advance for the duration of said block, and whether the DT appeared at the hand- (i.e. the movement's starting point) or target-location.

	Target Unknown				Hand Unknown				Mixed			
	Hand		Target		Hand		Target		Hand		Target	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
RT (ms)	472	124	462	117	504	135	496	117	538	149	536	137
MD (ms)	482	91	483	95	480	96	478	100	482	96	487	98
LA (mm)	16.7	4.78	16.1	6.29	17.1	9.87	15.9	6.41	20.5	7.49	18.7	9.92

While DT discrimination is commonly used as a measure of attentional performance, as it is measuring perceptual performance it is also an indicator of SfP rather than SfA. A possible measure of SfA could be given by the landing accuracy (LA) of the movement, which is likely to be influenced by how well the movement target was localised. A 3 (block type) X 2 (DT location) repeated measures ANOVA revealed that there was no effect of block type on movement accuracies ($F(2,28) = 1.93$ $p = 0.16$, $\eta_p^2 = 0.12$), so knowing in advance a feature of the upcoming movement did not appear to provide an advantage. The main effect of DT location on LAs also failed to reach significance ($F(1, 14) = 4.35$, $p = 0.056$, $\eta_p^2 = 0.24$). These

two main effects did not interact with one another ($F(2,28) = 0.12$, $p = 0.89$, $\eta_p^2 = 0.009$). It is interesting to note that the quality of the movement is not particularly good, which can be attributed to a lack of vision of the hand for movement guidance. As such landing accuracies may not be the most sensitive measure of attention.

When analysing the RTs, a 3 (block type) X 2 (DT location) repeated measures ANOVA found that there was a main effect of block type ($F(2,28) = 7.45$, $p = 0.003$ $\eta_p^2 = 0.35$), but not of DT location ($F(1,14) = 1.97$, $p = 0.18$, $\eta_p^2 = 0.12$), and these two did not interact with one another ($F(2, 28) = 0.43$, $p = 0.65$, $\eta_p^2 = 0.037$). As there was no effect of location on RTs, post hoc paired samples t-tests were run on the RTs for the different blocks, which showed that people were significantly slower in the mixed blocks than in the target unknown blocks (Mixed Blocks: M = 537ms, SD = 143 vs Target Unknown Blocks: M = 467ms, SD = 120; $p < 0.005$, d= 0.90). The RTs for the hand unknown blocks were in between those of the other two blocks (M = 500ms, SD = 125) and did not differ significantly from either one (Target Unknown: $p = 0.054$, $d = 0.54$; Mixed: $p = 0.057$, $d = 0.53$).

With regards to MDs, no significant effects were found for either block ($F(2,28) = 0.17$, $p = 0.85$, $\eta_p^2 = 0.012$) or DT location ($F(1,14) = 0.29$, $p = 0.60$, $\eta_p^2 = 0.02$), and they also did not interact with one another ($F(2, 28) = 0.43$, $p = 0.65$, $\eta_p^2 = 0.03$).

4.1.3.3 Additional Analyses: Differences between hands

There were a few additional analyses which, although not central to our research question, we decided to attempt to address with the data we had collected, and are discussed below. As the MD data had so far not yielded significant results, this was not analysed further in order to limit the number of analyses.

The first question one may have is whether participants may have differed in their movement performance between their two hands. All of our participants were right handed, and as such perhaps their dominant hand was either more accurate or quicker to respond. A paired samples

t-test on the LAs of the left (M = 18.14mm, SD = 6.50) and right hand (M= 16.54mm, SD = 5.84) found no significant differences between the two ($t(14) = 1.20$, $p = 0.25$, $d = 0.31$). Looking at RTs found a similar pattern: the RTs for the left (M = 504ms, SD = 121) and right hands (M = 499ms, SD = 133) also did not significantly differ from one another ($t(14) = 0.43$, $p = 0.68$, $d = 0.11$). There are thus no significant differences in the movement execution of either hand.

4.1.4 Discussion

Contrary to what we expected to see, we found no effect of the block types on the pattern in the allocation of attention. Regardless of the block type, more attention was allocated to the movement target than at the movement start point. The fact that the movement properties such as duration and landing accuracies were not influenced by the block type suggest that participants found the movements themselves as easy to execute regardless of the block type, which is in itself perhaps not surprising. One could have expected that, for instance, the higher unpredictability of the mixed blocks may have delayed not just the planning but also the execution of the movement. This may only occur when there is a higher number still of potential movements that could be executed. As mentioned above, the RT data did show an effect of block type. Unsurprisingly, having no advance knowledge of the type of movement they were going to execute (i.e. in a mixed block) produced the slowest RTs, which was to be expected as both arrow-cues needed to be interpreted prior to movement execution. Furthermore, work by Rosenbaum (1980) has found that the more parameters of an upcoming movement are unknown, the slower the resulting RTs. Rosenbaum also found that the delay introduced by each unknown component of a movement (e.g. choosing the effector, direction and/or magnitude of a movement) introduced differing amounts of delay, which also suggests that each component is computed differently. Taken together these findings suggest that advance knowledge of movement parameters can be used to plan components of a movement in advance, and our RT data fits with this too. That being said, our experimental design does

not allow us to distinguish between increases in the RTs due to having to interpret two of the cues as opposed to one, and there being more unknown movement parameters, as the former is a natural consequence of the latter. However if the slowest RTs in the mixed block are due to fewer movement components being planned in advance, it is surprising that we do not see differences in attentional allocation between the blocks in Experiment 1, since advance planning of manual movements allows people's attention to not be tied to the movement execution (Deubel & Schneider, 2003).

Experiment 1 had a crucial limitation which must be taken into account. Though it found that attention was allocated preferentially to the movement target, we do not know whether more attentional resources were also allocated to the starting point compared to other, non-movement relevant locations. It may be the case that even though we always found the target to receive more VSA than the starting location, discrimination performance at the latter may still be better than at the static hand or other locations in the visual landscape which may receive even less or no attentional resources. In Experiment 1, apart from trials in the mixed block, perceptual performance at the movements' starting point was significantly better than chance, so it may be possible that some VSA was allocated to it. Furthermore, even the results for the mixed blocks were trending in the direction one would have expected if attention was being allocated also to the starting point. On the basis of the findings of Reed et al. (2006) and the literature assessed in Chapter 3, one would expect that attentional performance at the hand locations to be above baseline, whether the hand is going to move or not. Our first experiment was not suited to replicate these findings due to the limited number of locations probed. Furthermore, a related question is whether a hand that is about to move receives more attention than a static one. Both of these questions can be addressed by probing attention not only at the movement relevant locations, but also on some trials at either the static hand or the non-target location. This was done in Experiment 2.

Increasing the number of locations the DT could appear at helped resolve another related issue, namely that on each trial participants knew that the DT would appear either at the movement's start or end location. This sort of knowledge may allow subjects to strategically allocate the majority of their attention to a particular location, and thus these results may be less likely to reflect the role of movement planning and execution in influencing the pattern in which VSA is allocated. As we have seen in Experiments 2-4 of the present thesis and Desimone and Duncan's biased competition account of attention (Desimone & Duncan, 1995), there are many factors which influence the way attention is allocated, be they exogenous or endogenous. It may be that this advance knowledge of the high likelihood that the DT will appear at the target location may override any role of effector-selection in shaping the attentional landscape. Increasing the number of locations a DT may appear at in any given trial would decrease the incentives for participants to strategically allocate attention to a specific location (such as the movement target), as this would coincide with the DT location only 25% rather than 50% of the time.

In summary, this first Experiment found that regardless of the block type, participants appeared to allocate more VSA to the movement target than to the movement's start point. The fact that attention is allocated to the target location is consistent with previous literature (e.g. Deubel et al., 1998), although we were surprised that advance knowledge of different movement parameters had no detectable effect on the way attention was allocated (e.g. Posner et al., 1980). At this point what remains an open question is whether more attention is allocated to the moving hand's starting point compared to other locations. Furthermore, the DT always appeared either at the end or start point of a movement, which may have encouraged subjects to strategically alter the way they would allocate their attention. These issues are tackled in Experiment 2.

4.2 Experiment 2: Probing more locations and changing the cues

4.2.1 Introduction

The main purpose of Experiment 2 was to probe the levels of attentional allocation at movement irrelevant locations as well as at movement relevant ones. For this reason in Experiment 2 the DT could appear in any of four locations: the movement's starting point, the movement target, the static hand and the non-target location. This contrasts with Experiment 1, where the DT appeared always either at the movement's start point or the movement target. This decreased the predictability of where the DT could appear at any given trial from 50% to 25%. Why is this important? Montagnini and Castet (2007) found that perceptual enhancement at an upcoming saccade target was the strongest when the DT had a high likelihood of appearing there, and weakened as the probability decreased. Furthermore, in a recent paper Hayward and Ristic (2013) found that the magnitude and time course of IOR can be modulated in a Posner task by altering the likelihood with which a target is going to appear. As our primary interest was to focus on the role of movement planning and execution in allocating attention, we were keen to decrease the contribution of advance knowledge as much as possible, while keeping it balanced across the different stimulus locations.

Just like the work by Montagnini and Castet (2007) highlights the role of prior knowledge of the DT location in the way VSA is allocated, we also expected to find it to be altered by the advance knowledge about some aspects about the upcoming movement. However we found no traces of such an effect of block type, and in order to avoid having too many trials, we only utilised the mixed block-format.

A final change between the first two experiments concerns the central cues used in both. Some previous work has found that arrows may lead to faster, reflexive shifts of attention (Brignani et al., 2009; Guzzon et al., 2010; Ristic & Kingstone, 2006). As our key aim was to investigate the role manual actions play in the allocation of attention, it was important to minimise the

size and number of other factors known to potentially influence the way attention is allocated. Furthermore, it may also be possible that less intuitive central cues may result in more attentional processing of movement-relevant location. With these things in mind, we decided to move away from using arrows in the next set of experiments (i.e. Experiments 2-4), and cue the movement target with the shape of the central cue (either a square or a circle), while cueing the movement hand with the colour of said cue (with either red or green). Having implemented these changes, we expected to find that not only was attention allocated to the movement target, but also that, though not as good, the performance at the movement's starting point was higher than at other locations (i.e. at the static hand and at the uncued target). In other words, we expected perceptual performance to be better at the *relevant* target and hand (i.e. the movement target and the movement's start point) than at the *non-relevant* target and hand (i.e. the uncued target and static hand). As we shall see, the different methodological changes did produce a different pattern of results than Experiment 1.

4.2.2 Method

4.2.2.1 Participants

Sixteen new participants (6 females, 10 males, mean age = 21.3 years SD = 2.10) took part in Experiment 2. They had all normal or corrected-to-normal vision (though no glasses as this interfered with the eye tracking) and were right-handed by self-report. All were reimbursed £6 for their time. This study was approved by the Psychology Research Ethics Committee, University of Edinburgh.

4.2.2.2 General Set-up

The experimental set-up was the same as that used in the first experiment. The only changes involve the arrangement of the stimuli. There were still four digital ‘8’s, two designated as potential targets and two as the starting points of the two hands, and they were of the same dimension as before. However instead of being placed at the corners of an imaginary 8.1° x

8.1° diamond, the 8s were located 8.1° above and below fixation and 8.1° to the left and right of fixation (see Figure 4.6 below). This was done in order to decrease the number of trials lost to missing kinematic data, which in Experiment 1 resulted from one of the hands obscuring the other one. This may have reflected horizontal movements moving across one's body. Although attention was found to be improved in the lower hemisphere, this was only for the movements' starting points. This should no longer be an issue in the current set-up as the hands are on the horizontal meridian.

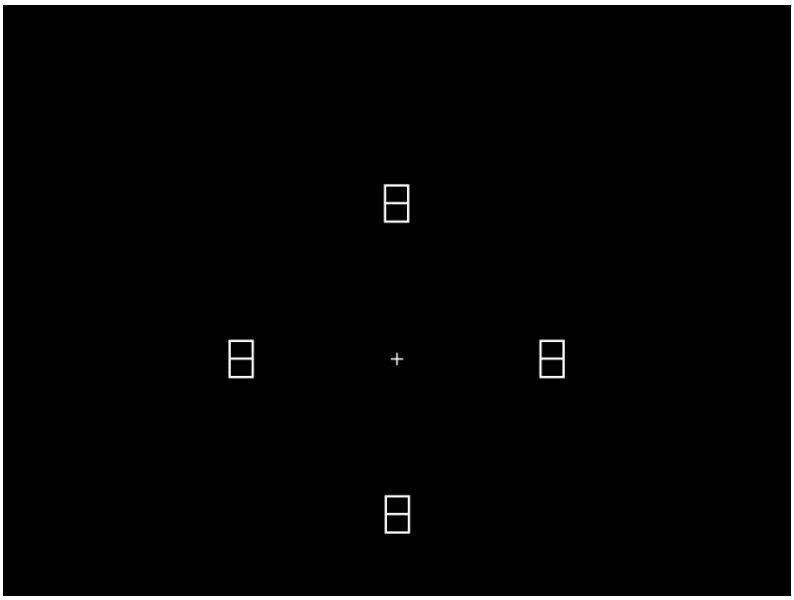

Figure 4.6. The re-arranged initial screen used in Experiment 2. Participants placed their hands on the 8s on the horizontal meridian, while the targets were on the vertical meridian.

A further major difference in the procedure was that instead of the target and movement hand being indicated by arrows, either a square or a circle which was either red or green was used. These were 0.8° and 0.9° in diameter respectively, and the luminosity of the colours was 18cd/m^2. These replaced a fixation cross (0.7° in diameter).

4.2.2.3 Procedure

But for a few differences, the procedure was the same as in Experiment 1, and can be seen below (Figure 4.7, p. 103). Subjects still had to point with the cued hand to the indicated target, and at the end of the trial report the identity of the DT. However, as stated above, the movement

instructions were provided not by arrows but by a square or circle appearing at fixation, which was either red or green. The colour indicated which hand was to make a movement, and the shape indicated the movement target. Which colour corresponded to which hand was counterbalanced between participants, as was the pairing between the shapes and the targets. Contrary to the first experiment the same manual set-up was used for all participants, who had their hands on the left and right 8s respectively, and the movement targets were the 8s located above and below fixation. A further difference was that the movement cues were displayed on the screen for longer, so as to provide more time for their interpretation (250ms instead of 200ms). The rest of the time course was identical to that used in Experiment 1. Subjects performed a practice (mixed) block of 32 trials, followed by 5 experimental blocks, also mixed, consisting of 32 trials each. A final difference was that in this experiment the DT was equiprobable in all of the four locations: the movement starting point, the movement target, the static hand and the non-target location.

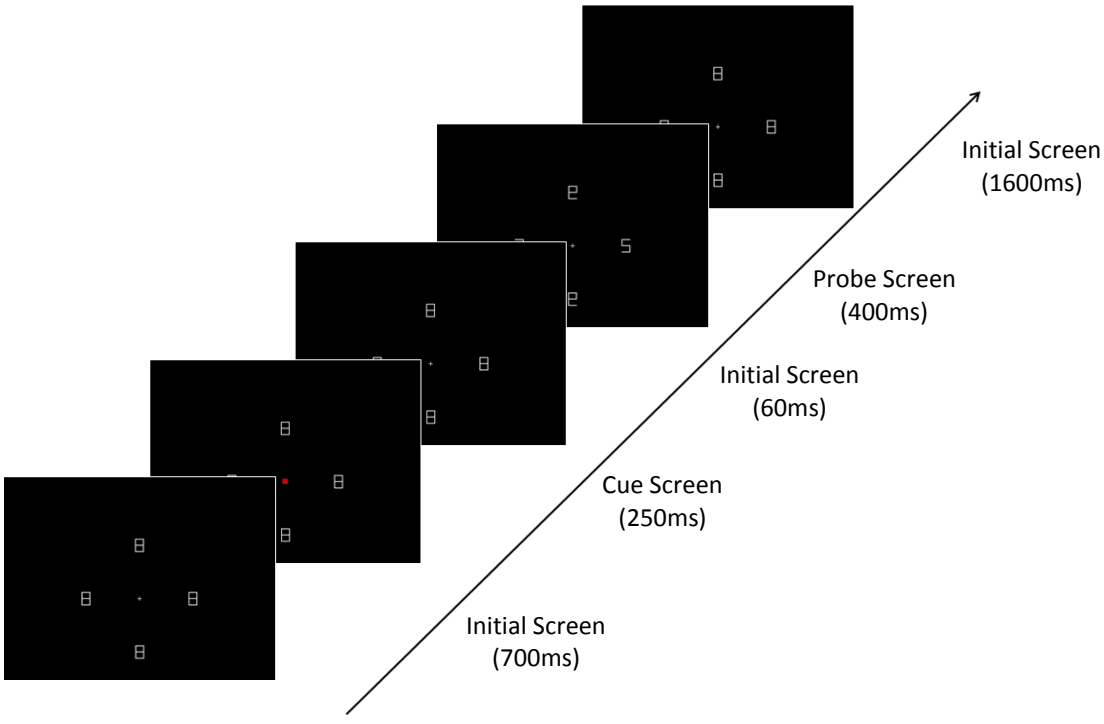

Figure 4.7. Trial sequence for Experiment 2. The trial sequence is the same as in Experiment 1, except that the cue screen was presented for 50ms longer than in the first experiment.

4.2.2.4 Data Treatment

The data were treated in a similar manner as in Experiment 1, but collapsed in a different manner. Trials were divided to according to whether the DT appeared at a potential effector (i.e. at one of the two hand locations) or potential target locations (Hand vs Target location), and whether that location was relevant to the movement executed on that trial or not (relevant vs non-relevant). This contrasts with Experiment 1, where the DT location was always 'relevant' i.e. the DT always appeared either at the movement's start or end point, whereas in Experiment 2 it could also appear by the static hand or at the non-target location.

Data filtering followed the same procedure as in Experiment 1. This lead to the removal of 1% of trials due to incomplete kinematic data, 11% due to the wrong move having been executed and 5% of trials removed because they did not fall within 2SD of each subjects' mean RT.

4.2.3 Results

4.2.3.1 Perceptual Performance

The DT-discrimination accuracies can be seen in Figure 4.8 (p.105). One can see that there is a striking difference between the results obtained in the Experiment 1, with performance at both hand locations being much higher than at the movement's start locations in the previous study, where perceptual performance was between 59-65%.

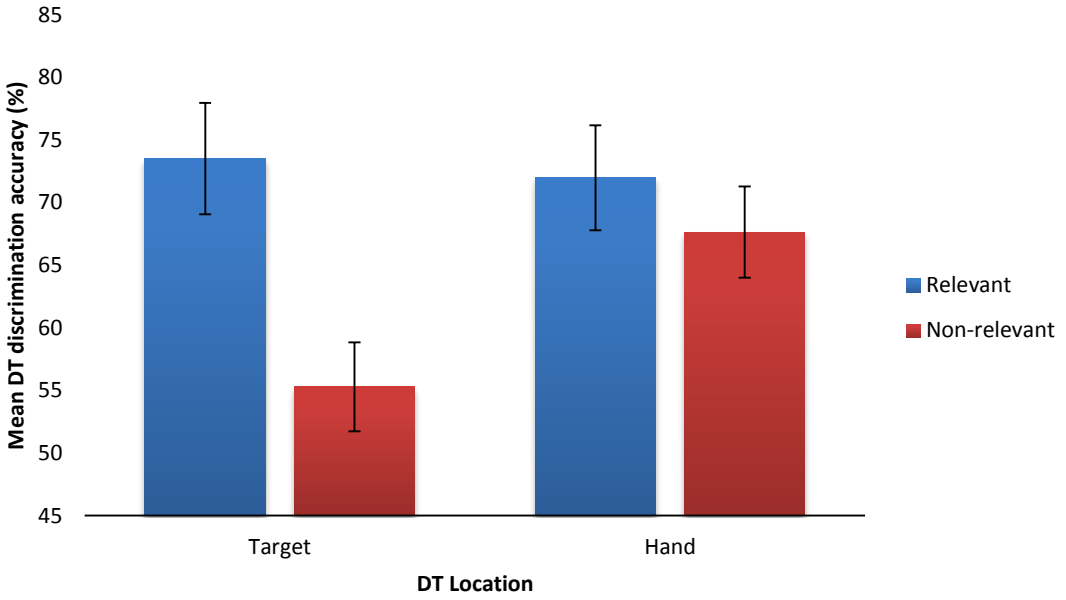

Figure 4.8. Mean discrimination accuracies at the different relative locations. The relevant target corresponds to the movement target, while the relevant hand corresponds to the movement's starting point. Meanwhile, the non-relevant target was the uncued target, while the non-relevant hand corresponded to the static hand. The error bars depict standard errors.

A 2 (hand vs target location) X 2 (relevant vs non-relevant) repeated-measures ANOVA found that there was a significant effect of 'relevance', with subjects' DT discrimination being enhanced at the relevant locations ($F(1,15) = 15.97$, $p = 0.001$, $\eta_p^2 = 0.52$). No main effect was found of whether the probe appeared at the hand or at the target location ($F(1,15) = 1.26$, $p = 0.28$, $\eta_p^2 = 0.078$), but the interaction between the two is significant, suggesting that the effect of relevance was more pronounced at the target than at the hand-location ($F(1,15) = 5.02$, $p = 0.041$, $\eta_p^2 = 0.25$). The data shows that contrary to the findings in Experiment 1, attention was allocated not only to the relevant target, but also to the starting point of the movement (i.e. the relevant hand).

In order to better explore these results and the overall distribution of attention, a set of post hoc paired-samples t-tests were conducted. As can be seen depicted in Figure 4.8, there was no significant difference between discrimination performance at the two relevant locations ($t(15) = 0.28$, $p = 0.78$, $d = 0.07$), which is in marked contrast to the findings from Experiment 1. What was arguably more surprising was that the DT-discrimination levels observed at the

static hand were *not* significantly worse from the levels of performance observed at the relevant hand (i.e. the movement's starting point) ($t(15) = 1.38$, $p = 0.19$, $d = 0.34$), or at the relevant target ($t(15) = 1.05$, $p = 0.31$, $d = 0.26$). However perceptual performance at the non-relevant target was significantly worse than at the non-relevant hand ($t(15) = 2.99$, $p = 0.009$, $d = 0.75$). One-sample t-tests showed that perceptual performance at the non-relevant hand was significantly better than chance ($M = 67.6\%$, $SD = 14.2$; $t(15) = 4.39$, $p = 0.001$, $d = 1.10$), whereas performance at the non-relevant target was not ($M = 55.3\%$, $SD = 14.6$; $t(15) = 1.49$, $p = 0.16$, $d = 0.069$). Thus the overall distribution of attention appears to be considerably wider than we would have expected from Experiment 1, with of the probed locations, only the non-relevant target failing to show evidence of atentional allocation.

Overall these results point to a much more widely distributed perceptual enhancement than that seen in Experiment 1. For instance in the first experiment, trials in the mixed blocks where the DT appeared at the movements' starting location, perceptual performance was not significantly better than chance ($M = 58.7\%$, $SD = 20.3$; $t(14) = 1.27$, $p = 0.23$, $d = 0.33$). This is in sharp contrast with the better-than-chance performance at the relevant hand location seen in Experiment 2 ($M = 73.0\%$, $SD = 16.8$; $t(15) = 4.64$, $p < 0.001$, $d = 1.16$). As the DT location was less predictable in the second experiment, the way attention was allocated on each trial may have been more influenced by action planning rather than advance knowledge of the likely upcoming DT location (Montagnini & Castet, 2007).

4.2.3.2 Motor Performance

The cloud of movement end-points can be seen in Figure 4.9 (p. 107). The mean overall landing accuracy was 16.54mm ($SD = 8.62$). The descriptives for the different movement parameters at the different relative locations can be seen in Table 4.2.

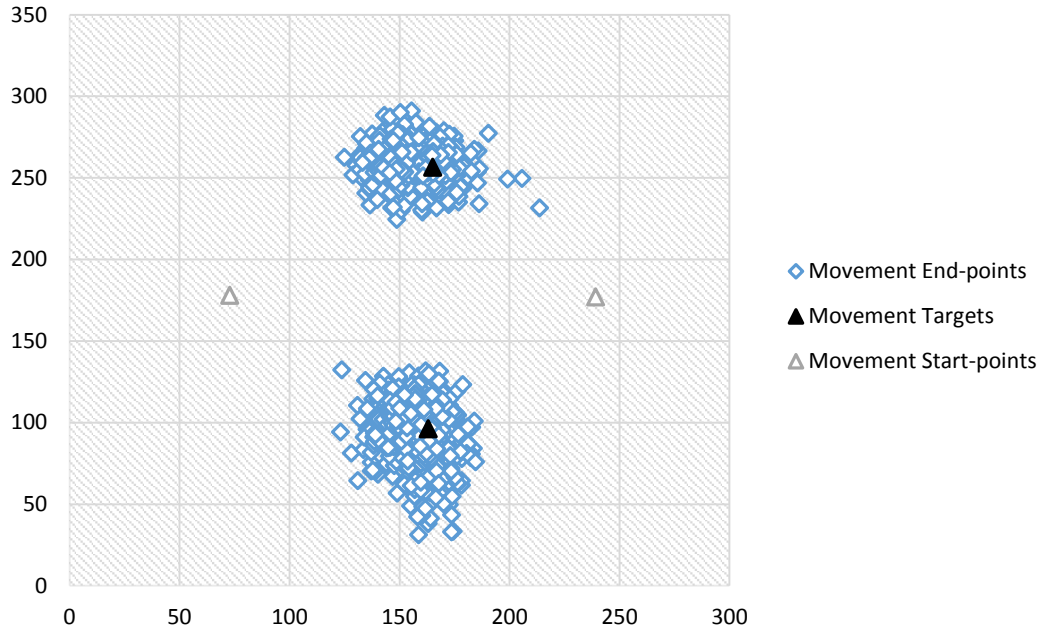

Figure 4.9. Overall movement end-, start-points, and calibrated movement targets. Both axes are in mm.

Table 4.2. Means and SDs for the different relevant and non-relevant RTs. Although no main effects were significant for any of the movement variables, for RTs there was a significant interaction between relevance and location, with fastest times when the DT appeared at the relevant hand and slowest when it appeared at the non-relevant hand ($p < 0.036$). These times are highlighted in bold.

	Relevant Hand		Relevant Target		Non-relevant Hand		Non-relevant Target	
	M	SD	M	SD	M	SD	M	SD
RT (ms)	**662**	132	674	126	**681**	151	675	142
MD (ms)	366	81	369	78	367	79	368	85
LA (mm)	16.4	2.44	16.7	3.39	16.2	2.91	16.6	3.55

Were the LAs influenced by the DT location in Experiment 2? A 2 (hand vs target) X 2 (relevant vs non-relevant) repeated measures ANOVA found that this was not the case. Neither the effect of relevance ($F(1,15) = 0.19$, $p = 0.67$, $\eta_p^2 = 0.013$) or of location ($F(1,15) = 0.35$, $p = 0.56$, $\eta_p^2 = 0.023$) significantly influenced LAs. Furthermore, they also did not interact with one another ($F(1, 15) = 0.004$, $p = 0.95$, $\eta_p^2 < 0.001$). None of these results indicate that the LAs were influenced by the location in which the DT appeared, and as such the results from Experiment 1 may have to be treated with some caution. However a slightly different pattern emerged when analysing the RTs, but again one which should be interpreted with care.

A 2 X 2 repeated measures ANOVA conducted on the RTs found no main effect of either relevance ($F(1,15) = 2.16$, $p = 0.16$, $\eta_p^2 = 0.13$) or of whether the DT appeared at a hand or target location ($1,15) = 0.18$, $p = 0.68$, $\eta_p^2 = 0.012$). However these two factors did interact significantly with one another ($F(1,15) = 5.02$, $p = 0.041$, $\eta_p^2 = 0.25$). A post hoc paired-samples t-test showed that subjects were significantly faster when the DT appeared at the movement's start location ($M = 662$ms, $SD = 132$) compared to when the DT appeared by the static hand ($M = 682$ms, $SD= 151$) ($t(15) = 2.31$, $p = 0.036$, $d = 0.58$) (the RTs of trials in which the DT appeared at the relevant or non-relevant targets were in between these means). The speeding up of RTs when the DT appeared by the responding hand may have been resulted by the congruence of the two tasks, while the incongruence of the DT appearing at the static hand may have slowed the execution of the movement. The fact that both hand locations were attended can be seen by the high DT discrimination levels at both, and would support such an interpretation.

A 2 X 2 repeated measures ANOVA found no main effect of relevance ($F(1,15) < 0.001$, $p > 0.99$, $\eta_p^2 < 0.001$) or location ($F(1,15) = 0.33$, $p = 0.57$, $\eta_p^2 = 0.022$) on MDs, and neither did these two factors interact with one another ($F(1, 15) = 0.099$, $p = 0.76$, $\eta_p^2 = 0.007$).

4.2.3.3 Additional Analyses – Hands and pre-movement shifts of attention

As with Experiment 1, paired-samples t-tests failed to find any differences in either the RTs ($t(15) = 0.44$, $p = 0.66$) or LAs ($t(15) = 1.11$, $p = 0.29$) between the left and the right hand.

The RTs were slightly higher in Experiment 2 than they were for the mixed blocks in Experiment 1 ($M = 538$ms, $SD = 138$), which may have been due to the use of less familiar central cues in Experiment 2 (i.e. red and green circles and squares rather than arrows). This meant that there were fewer trials in which the DT was still on screen at movement onset, which provided us with an opportunity to assess solely trials in which movement onset was after DT offset. When one filters out the trials in which the DT offset occurred before movement onset, this resulted in the removal of 53.6% of the trials. Only data from subjects

who had more than 10 trials for each of the four trial types (when the DT appeared at the movement target, at the movement starting point, at the static hand or at the non-relevant target) were analysed, which left us with only 8 subjects. Following this additional filtering process, a 2 X 2 repeated measures ANOVA with relevance and location as factors was again conducted. Although the results of whether a location was relevant to a movement were in the expected direction (i.e. better performance at the relevant locations), this effect failed to reach significance ($F(1,7) = 5.35$, $p = 0.054$, $\eta_p^2 = 0.43$). Whether the DT appeared at the hand or target location was also not significant ($F(1,7) = 0.69$, $p = 0.43$, $\eta_p^2 = 0.09$), and neither was the interaction between the two ($F(1,7) = 0.50$, $p = 0.50$, $\eta_p^2 = 0.067$). Inability to achieve significant results may not be that surprising considering the number of excluded trials and participants.

4.2.4 Discussion

The main aim of the current experiment was to assess how attentional performance at the movement's starting point compared to locations not relevant to the movement being carried out. Two major changes made to the methodology from Experiment 1 were decreasing the predictability of where the DT could appear, and swapping the cues from arrows to coloured shapes. These changes had drastic effects on our results, with the most critical being that attention was allocated to all locations relevant to the movement. This findings support our initial hypothesis that in an appropriate experimental paradigm, all relevant locations to a movement are attended, not just the movement target.

It is difficult to ascertain which methodological change was most responsible for the difference in results between Experiments 1 and 2. It is possible that the replacement of the arrows played a part, and it is the most likely reason for slower RTs, as less familiar cues would take longer to interpret. However the presence of two arrows indicating the two relevant locations would have ensured that any effects resulting purely by the properties of the arrows would have been equal at both locations. Nevertheless the arrows also allowed for a quick identification of the

two locations the DT was likely to appear at, and participants may have an endogenous strategic bias to allocating more attention to the movement target. The hardest question to answer is why participants would have such a bias when the probe was equally likely to appear at both the target and starting locations. There are two factors to consider, the first one being that any such endogenous bias may only be present when the DT has a relatively high likelihood of appearing at a specific location (Montagnini & Castet, 2007), and thus providing motivation to strategically attend some place. As to why participants would then consistently opt to allocate these 'strategic resources' to the target location may be that it will remain relevant for longer than the movement's starting location. After all after movement initiation the starting point will no longer be relevant, whereas the target remains relevant throughout the movement.

In contrast, in Experiment 2 the movement location is not predictive of DT location, which may have been disincentive enough for participants to not preferentially attend to the target location. This interpretation will supported by the results obtained in Experiment 3 and 4. Ironically, while one of the main aims of Experiment 1 was to observe the role of advance knowledge of the upcoming movement in the allocation of attention, these results do appear to indeed show an effect of advance knowledge, but that of the probable location of the upcoming DT.

The present experiment also provides interesting results regarding the non-relevant locations, more specifically the static hand. Not only was performance significantly better than at the non-relevant target, it actually was as good as at the relevant hand location. The case for attentional resources being also allocated to the static hand becomes stronger when considering that the appearance of the DT at the static hand disrupted the movement's RT, something that would only occur if it had been attended to on some level. Thus the case is persuasive for attentional resources being allocated also to the static hand, consistent with previous work (e.g. Reed et al., 2006; Adam et al. 2012; Abrams et al., 2008).

Although we found a main effect of 'relevance', on closer scrutiny this effect is not as robust as one would initially think. As presaged by the significant interaction between relevance and location (i.e. whether the DT appeared at a target- or hand-location), the difference between the perceptual performance at the moving and static hands was not significant, although the difference was in the expected direction. Perhaps the difference in performance between the moving/relevant and static hands is diminished by the length of time the DT was presented for, and shorter presentation times would highlight the difference between the two. The results from Experiment 3 will support this view.

4.2.5 Serial or parallel shifts of VSA?

Experiment 2 found enhanced perceptual performance at several locations, but are these attended in a serial or parallel fashion? In order to compute an action you may first have to know where one is coming from, and it is possible that attention is first allocated to the starting point of the movement. This might explain why the fastest RTs were observed when the DT appeared at the movement's start point, as earlier completion of the perceptual task may free cognitive resources for the execution of the motor task. However, the slowest RTs were observed when the DT appeared at the static hand. This latter finding suggests that the appearance of the DT by the static hand may disrupt the planning of the movement, which in turn means that it was also attended as otherwise the RT would not have been slowed down. That attention was allocated to the non-relevant hand is something that we saw reflected in the subjects' perceptual performance. This would then suggest a parallel allocation of attention at least as far as the hand locations are concerned. Abrams et al. (2008) did find that hands slowed down the allocation of attention away from the hands. That the appearance of the DT at non-hand locations did not influence the RT could suggest that both hand locations are attended before the target. It is still possible that the target needs to be identified before the appropriate effector is selected, and as such the processing of the target may be start first. There is however also a third alternative, which is that attention is allocated in parallel to multiple locations,

both by the hands and target. Experiment 3 was designed to shed light on this question, while also providing more information on the potential relationship between the static hand and VSA.

4.3 Experiment 3: Sequential allocation of attention?

4.3.1 Introduction

Contrary to Experiment 1, Experiment 2 found no difference in attentional allocation between the movement target location and the movement start location, with DT detection accuracy being enhanced equally at both rather than just at the target location. This discrepancy between the results of the first two experiments may be due to differing amounts of uncertainty with regards to the location of the DT, leading subjects to strategically focus more attention to the movement target in Experiment 1. Not only did Experiment 2 find equally good perceptual performance at both movement-relevant locations, it also found better than chance performance at the location of the static hand. A question that arises is whether VSA in Experiment 2 was allocated across the visual landscape in a serial or parallel manner. For instance with regards to movement-relevant locations, did subjects systematically attend first to where they were going or to their starting position? Alternatively, attention could have been allocated in parallel to multiple locations.

In order to address this question we repeated Experiment 2, but shortened the DT-presentation time to 300ms, and presented it at one of two different times after the cue: either at cue offset (0ms) or 200ms after. If either of the movement locations is consistently attended to first, then DT discrimination should be better at that location when the DT appears there at cue offset, than when it appears 200ms later. For instance, in order to compute the appropriate movement parameters subjects might need to focus their attention first at where they are initiating their movement from. This would result in DT-discrimination being better at the movement start-point than at the movement endpoint on trials where it appeared at cue offset. The reverse findings would instead support the view that attentional priority is given first to the movement target. Finally, if attention is allocated in parallel to multiple locations, or serially but without fixed ordering, then one would expect there to be no interaction between the timing of the DT

and the location it appeared at. These projected patterns of results and interpretations of them naturally hinge on the assumption that the results from Experiment 2 can be replicated in the first place. Experiment 3 therefore also served the purpose of strengthening the findings obtained in Experiment 2, including assessing performance at the static hand location.

4.3.2 Method

4.3.2.1 Participants

Sixteen new participants (9 females, 7 males, mean age = 21.8 years SD = 2.21) took part in Experiment 3. They had all normal or corrected-to-normal vision (though no glasses as this interfered with the eye tracking) and were right-handed by self-report. All were reimbursed £6 for their time. This study was approved by the Psychology Research Ethics Committee, University of Edinburgh.

4.3.2.2 General Set-up

The same set-up was used as in Experiment 2.

4.3.2.3 Procedure

The procedure was in most respects the same as in Experiment 2. The main difference was that the DT target and distractors were presented for 300ms, either directly after cue offset (*early* trials), or after 200ms (*late* trials). As in the previous experiment, subjects first conducted a 32-trial practice block, followed by 6 blocks of 32 trials each, half of which had the probe appearing at cue offset, and half appearing 200ms after cue offset.

4.3.2.4 Data treatment

Trials were collapsed in the same way as Experiment 2, with the exception that they were also divided according to whether the probe appeared early or late.

Two percent of trials were excluded due to incomplete kinematic data, 14% due to the wrong move having been executed and 4% were removed because they did not fall within 2SD of each subjects' mean RT.

4.3.3 Results

4.3.3.1 Perceptual Performance

The main difference between Experiment 2 and 3 was that the DT could appear at two time points: either at cue offset (*early* trials), or 200ms later (*late* trials). If one of the two locations was systematically attended to first, then perceptual performance ought to be better at that location in the early-onset trials. However we conducted a 2 (early vs late) X 2 (hand vs target) X 2 (relevant vs non-relevant) repeated measures ANOVA, which found no main effect of the time at which the DT appeared ($F(1,15) = 2.21$, $p = 0.16$, $\eta_p^2 = 0.13$). Furthermore this factor did not interact with any of the others ($p > 0.12$). Thus we could not find evidence for serial shifts of attention and for this reason the time at which the DT appeared will not be considered further in these analyses on perceptual performance. The discrimination accuracies per condition (excluding the early vs late distinction) can be seen in Figure 4.10 (p. 115).

Once again, a 2 (hand vs target) X 2 (relevant vs non-relevant) repeated measures ANOVA found that more attention was allocated to a relevant location over a non-relevant one ($F(1,15) = 23.70$, $p < 0.001$, $\eta_p^2 = 0.61$). We also found a significant main effect of whether the DT appeared at a hand- or target-location ($F(1,15) = 20.26$, $p < 0.001$, $\eta_p^2 = 0.58$). However, as can be seen in Figure 4.10 below, performance was best at the hand locations rather than at the target locations. As the first two experiments had found perceptual performance at the relevant hand to be worse or as good as perceptual performance at the movement target, this was initially unexpected, but on reflection is consistent with previous literature (e.g. Abrams et al., 2008) and will be elaborated upon in the discussion section below. These two main effects did not significantly interact with one another ($F(1,15) = 0.23$, $p = 0.64$, $\eta_p^2 = 0.015$).

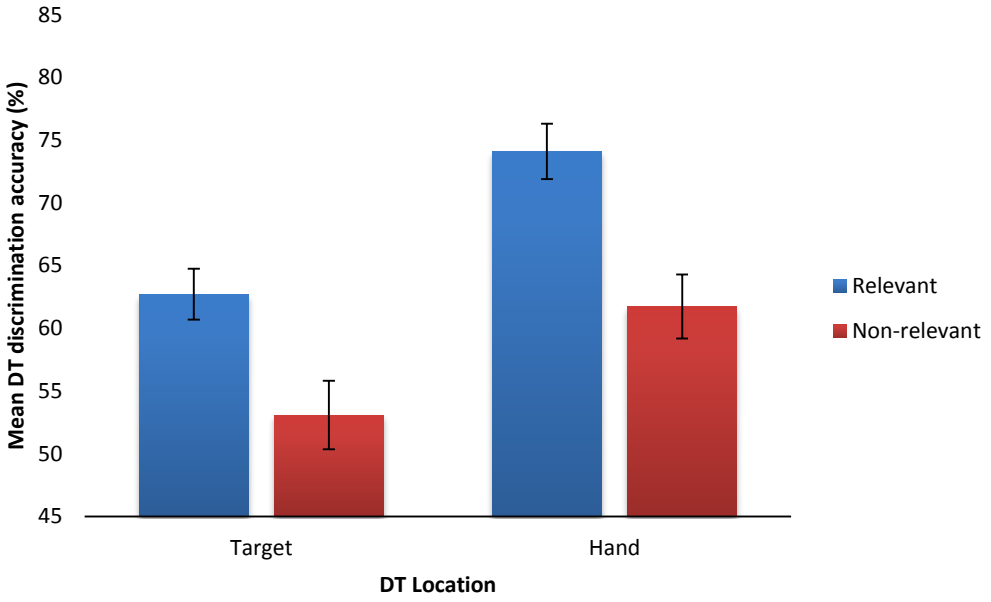

Figure 4.10. DT discrimination accuracies per location and relevance. Contrary to previous experiments, best performance was achieved at the relevant hand location (i.e. the movement starting point). Error bars represent standard errors.

Post hoc paired-samples t-test found that perceptual performance at the relevant hand was significantly better than performance at either the relevant target ($t(15) = 3.53$, $p = 0.003$, $d = 0.88$) or non-relevant hand ($t(15) = 3.34$, $p = 0.004$, $d = 0.84$), while performance between the latter two did not differ significantly between one another ($t(15) = 0.57$, $p = 0.57$, $d = 0.14$). Meanwhile performance at the non-relevant target was significantly worse than performance at the relevant target ($t(15) = 4.20$, $p = 0.001$, $d = 1.05$).

Furthermore, a one-sample t-test revealed that perceptual performance at the non-relevant target location did not differ significantly from chance ($M = 53.1\%$, $SD = 8.82$; $t(15) = 1.39$, $p = 0.19$, $d = 0.35$). In contrast, the best performance at the movement's start point did ($M = 74.1\%$, $SD = 10.9$; $t(15) = 8.09$, $p < 0.001$, $d = 2.02$), as did performance at the relevant target location ($M = 62.7\%$. $SD = 8.1$; $t(15) = 5.96$, $p < 0.001$, $d = 1.49$) and at the non-relevant hand location ($M = 61.7\%$, $SD = 10.2$; $t(15) = 4.33$, $p = 0.001$, $d = 1.08$). This pattern of results is very intriguing, also considering that the performance at both the relevant and non-relevant hands is very similar to that observed in Experiment 2 (73.0% and 67.6% respectively). One might have assumed that the shorter DT presentation time would have led to worse levels of

performance than in Experiment 2. Another interesting feature of the data is how performance at the relevant target location is no longer as good as at the relevant hand. We will be elaborating on both of these points in discussion section 4.3.4 (p. 119).

4.3.3.2 Motor Performance

The landing end points can be seen below in Figure 4.11. The overall mean distance between the targets and the movement end-points is 17.9mm (SD = 10.9), which is similar to that seen in the other experiments so far. The means and SDs of the different movement parameters broken down by the relative DT location and by whether the DT appeared early or late can be seen in Table 4.3 (p. 117).

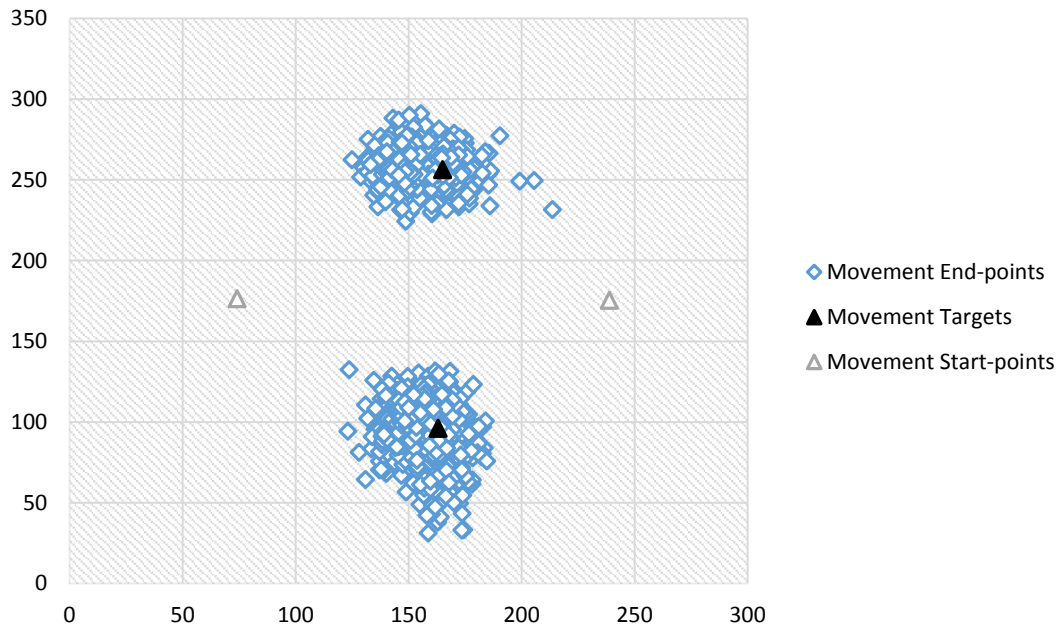

Figure 4.11. Overall movement end- and start-points and calibrated movement targets for Experiment 3.

We could not find any evidence for serial allocation of attention in the perceptual data, but it was possible that the movement data could reveal a different result. We thus conducted a series of 2 (early vs late) x 2 (relevant vs non-relevant) X 2 (hand vs target) repeated measures ANOVAs on RTs, MDs and LAs. Like for perceptual performance, the time at which the DT appeared had no significant effect on the RTs ($F(1,15) = 0.41$, $p = 0.53$, $\eta_p^2 = 0.027$), MDs

(F(1,15) = 0.24, p = 0.63, η_p^2 = 0.016) or LAs (F(1,15) = 0.52, p = 0.48, η_p^2 = 0.034). Furthermore, the time also did not interact significantly with any of the other effects on any of these movement variables (p > 0.22). For this reason, like with the perceptual data, this factor will no longer be considered in further movement analyses.

Table 4.3. Mean and SD for the different movement parameters at the different locations, divided by whether the DT was presented early or late.

	Relevant Hand		Relevant Target		Non-relevant Hand		Non-relevant Target	
	M	SD	M	SD	M	SD	M	SD
					Early			
RT (ms)	732	171	711	154	715	168	722	155
MD (ms)	358	36	356	45	360	41	357	32
LA (mm)	17.8	4.46	17.2	5.46	18.5	5.67	17.1	4.02
					Late			
RT (ms)	737	149	723	138	726	152	722	134
MD (ms)	356	34	358	42	364	42	358	45
LA (mm)	18.1	4.88	17.8	4.67	17.8	4.41	17.9	4.81

A 2 (relevant vs non-relevant) X 2 (hand vs target location) repeated measures ANOVA on the LAs however did not find a significant effect of either relevance (F(1,15) = 0.12, p = 0.73, η_p^2 = 0.008) or of location (F(1,15) = 3.56, p = 0.079, η_p^2 = 0.19), and they also did not significantly interact with one another (F(1,15) = 0.083, p = 0.78, η_p^2 = 0.006). These results are similar to those obtained in Experiment 2, and thus suggesting that the LAs are not influenced by the DT location.

A 2 (relevant vs non-relevant) X 2 (hand vs target location) repeated measures ANOVA as conducted on the RTs also failed to find a significant effect of relevance (F(1,15) = 0.34, p = 0.57, η_p^2 = 0.022) or location (F(1,15) = 0.74, p = 0.40, η_p^2 = 0.047), and again these two factors did not interact significantly with one another (F(1,15) = 1.19, p = 0.29, η_p^2 = 0.073). This does contrast with the findings in Experiment 2, where the interaction between these two factors was found to be significant (p = 0.041). The results from the present experiment cast

doubt on the validity of those findings, although it may be possible that in order for the DT to have an effect at either hand location, it needs to be present for longer.

A final 2 (relevant vs non-relevant) X 2 (hand vs target location) repeated measures ANOVA confirmed what we have seen in the experiments so far. The MDs were again unaffected by either relevance ($F(1, 15) = 0.88$, $p = 0.36$, $\eta_p^2 = 0.055$) or location ($F(1,15) = 0.41$, $p = 0.53$, $\eta_p^2 = 0.027$) and the interaction between these factors was not significant ($F(1,15) = 0.58$, $p = 0.46$, , $\eta_p^2 = 0.037$). This suggests that the online movement execution itself may not be much affected by the perceptual task. That being said, the movement performance on the whole in Experiment 3 seems to have remained largely unaffected by the location or point in time in which the DT appeared.

4.3.3.3 Additional analyses – Hands and pre-movement shifts of attention

Once again, there was no significant difference in RTs ($t(1,15) = 0.56$m, $p = 0.58$, $d = 0.14$) or in landing accuracies ($t(15) = 0.24$, $p = 0.82$, $d = 0.059$) between the two hands.

As in Experiment 2, RTs were higher than those seen in Experiment 1. This meant that for most of the trials analysed, movements started after DT-offset (80%), and the proportion of these were very similar for both early- and late-trials (79% and 81% respectively). Considering how Experiment 2 found no differences in the pattern of DT-discrimination between trials in which the DT was present or not at movement onset, one would expect that to be still the case in Experiment 3. As for Experiment 2, after removing the 20% of the trials in which the DT overlapped with movement onset, we removed from the analysis participants who had less than 10 trials remaining per trial type. This left us with 12 participants. However analysing this filtered data did not produce any novel findings. A 2 (early vs late) X 2 (relevant vs non-relevant) X 2 (hand vs target location) repeated measures ANOVA once more failed to find an effect of whether the DT appeared late or early ($F(1, 11) = 1.45$, $p = 0.25$, $\eta_p^2 = 0.12$), while performance was better at relevant locations compared to non-relevant ones ($F(1,11) = 20.37$,

$p = 0.001$, $\eta_p^2 = 0.65$) and at the hand locations over the target ones ($F(1,11) = 8.29$, $p = 0.015$, $\eta_p^2 = 0.43$).

4.3.4 Discussion

As in the previous experiment, Experiment 3 found that attention is allocated to both movement-relevant locations assessed in these experiments: the movement's end and starting point. This is important as it helps consolidate the findings of Experiment 2. Furthermore, Experiment 3 found no significant interaction between the relevance of a location and whether it was a hand or target location. Thus this provides less ambiguous evidence for attention being allocated preferentially to all movement-relevant locations. However, arguably the lack of any effects of the time course in which the DT appeared that provides even more insights. The main objective of the present experiment was to investigate whether attention was being allocated to the different locations in a serial or parallel fashion by testing whether changing the onset-time of the DT. The lack of any effect of this manipulation supports the parallel account and is consistent with findings of prior literature (e.g. Baldauf et al., 2006; Festman et al., 2013a, 2013b; Awh & Pashler, 2000; Feng & Spence, 2013; Jefferies et al., 2013). It is worth pointing out though that our experiments do not probe the visual landscape in enough detail to differentiate whether a unitary focus of attention or multiple non-contiguous attentional enhancements were taking place.

It is possible that attention was serially shifted from one location to the next. However participants in Experiment 1 had only two potential DT-locations and 400ms to shift their attention to both, and yet performed well only at the target location. If attending to multiple locations in such a time frame, whether serially or in parallel, was easy, then we would have expected better performance at the starting location in Experiment 1. If serial shifts of attention are behind the pattern of our results, then they are not occurring in a systematic order.

The parallel account of attentional allocation also fits another aspect of the results: that attention was not only enhanced at the movement-relevant location, but also at the static hand's

location, thus increasing the number of attended locations to three. This raises the question of why overall performance at the hand locations is better in Experiment 3 than at the target location, contrasting what we have seen in the preceding experiments. A possible answer is that even though the allocation of attention to multiple locations may be occurring in parallel, it is not necessarily happening at the same rate at all locations. The rate at which attention is allocated to the different locations may be influenced by the sum of different attentional orienting mechanisms acting at each one. As we know since the work by Deubel et al. (1998) attention is allocated to the target of a manual movement, and more recent work by Festman and colleagues (2013a, 2013b) has shown that attention is allocated also along the movement path. However we also know that attention is allocated to events occurring in a person's peripersonal space, especially the hands (e.g. Reed et al., 2006; Graziano & Gross 1995). We therefore know that attentional allocation is influenced by both these factors, which may explain why attentional allocation occurs also at the static hand, and indeed we saw this effect replicated in Experiment 2. However we still need an explanation as to why the performance at the hands was better than at the target location in Experiment 3 while the opposite was the case in Experiment 2?

An explanation for this may come from the work of Abrams et al. (2008) covered in Chapter 3 (p. 75), which found that the presence of the hands near the screen slowed down the disengagement of attention from the areas near them, as illustrated by slower search times, reduced IOR-effects and increases in the length of the attentional blink (see also Davoli & Brockmole, 2012). In other words, attention at other locations is slowed down compared to the area surrounding the hands. However this does not imply that all attentional resources are therefore allocated first only to the hands, as indeed otherwise we would observe better DT discrimination accuracies at the starting location for early-trials. This is because while we may have one mechanism pushing for the allocation of attention to one's peripersonal space (in this case the hands), we simultaneously have a separate mechanism driving the allocation of

attention to movement-relevant locations. A crucial detail regarding the differences between the two experiments is that the DT is present for 100ms less in Experiment 3. Although the two attentional processes may therefore be occurring additively at each location in parallel, the rate of attentional allocation to the relevant target is at first slowed down. At shorter presentation times (Experiment 3) relatively more attention has time to accrue at the hand locations. However as the presentation time of the DT increases, the attentional pull of the hands ceases to have an effect and more attention has time to accrue elsewhere. In the case of Experiment 2, this would be at the movement target. The similar discrimination performance observed at the relevant hand location (Exp. 2: 73% vs Exp 3: 74.1%) and the non-relevant hand locations (67.6% vs 61.7%) are in accordance with this view, and may represent the sum of the total attentional resources the relevant and non-relevant hands may be allocated. In other words, Experiment 3 could be considered to be like an early snapshot of the development of the pattern of the results seen in Experiment 2. This may also have resulted in a cleaner effect of relevance on perceptual performance, as the effect has less time to interact with the attentional pull of the hands. The reason why the effect of the hands was not evident in Experiment 1 may have been that it may have been overridden by participant's strategies, such as preferentially attending to a likely DT-location which will remain relevant for longer (i.e. the movement target). Also, in the experiments seen so far, perceptual performance has not been better at the static hand compared to the other, relevant locations. The attentional capture by the hand may therefore not be that strong and may be more easily overridden, which may also explain the pattern of results in Experiment 1.

As stated before, the lack of an interaction between the DT-location and whether the DT appeared early or not does not support a serial shift of attention taking place in the present paradigm. Although speculative, the account provided above regarding the interplay of two separate mechanisms for orienting attention working in parallel neatly accounts for our data. Experiment 3 also replicates the effect that the action-relevance of a location has in drawing

attention to it, which includes the movement's starting location. With this latter point consolidated, we decided to re-attempt tackling the question posed in Experiment 1: the effect that advance knowledge of different components of an action has in influencing where attention is allocated.

4.4 Experiment 4: Revisiting Experiment 1

4.4.1 Introduction

Contrary to Experiment 1, the findings from Experiment 2 and 3 found attentional enhancement at the starting point of the movement, and Experiment 3 found that this actually surpassed the amount of attentional enhancement allocated to the movement target. These experiments also found that attentional resources were also allocated to the static hand, as one might predict from the work done by Reed et al. (2006) among others. The results obtained so far clearly show that the starting hand position is attended, but they do not distinguish whether this *always* occurs, or whether it only occurs when the hand must be selected for responding at the time of movement. We therefore aimed to re-visit the original question of whether advance knowledge of either the movement target or the moving hand influences the allocation of attention, but incorporating changes to the paradigm adopted in in Experiments 2 and 3: the DT could appear at any of the four locations (i.e. the relevant target, the relevant hand, the non-relevant target, and the non-relevant hand), and the movement instructions were provided by more abstract cues than arrows (i.e. red and green squares and circles). This was done in order to minimise the contribution of advance knowledge of the likely DT-location or arrow cues in determining where attentional resources were allocated (Hayward & Ristic, 2013; Montagnini & Castet, 2007; Ristic & Kingstone, 2006). In order to allow easier comparison to Experiment 3, the DT-presentation time was kept at 300ms. We once again expected to find differential patterns of perceptual enhancement depending on the block type, with further enhancement at unknown component of the movement. Our new attempt did indeed provide us with a different set of results than Experiment 1, but not in the manner we expected.

4.4.2 Method

4.4.2.1 Participants

Sixteen new participants (10 females, 6 males, mean age = 21.8 years, SD = 3.15) took part in Experiment 4. They all had normal or corrected-to-normal vision (though no glasses as this interfered with the eye tracking) and were right-handed by self-report. Testing was conducted in two sessions, and all were reimbursed £6 per session (£12 in total). This study was approved by the Psychology Research Ethics Committee, University of Edinburgh.

4.4.2.2 General Set-up

The same set-up was used as in Experiments 2 and 3.

4.4.2.3 Procedure

The procedure was in most respects the same as in Experiment 3. The DT was presented for 300ms so as to facilitate comparison with it, and it was presented directly after the cues, like in the early-trials seen before. Subjects conducted only trials where they either knew the movement target or the moving hand in advance. Both were determined at the block-level, with the type of block alternating and the order counterbalanced between participants. Each block was preceded by a practice block of 8 trials, except for the first one which was preceded by a practice block of 32 trials.

4.4.2.4 Data treatment

The data was treated in a similar way as in the previous experiments. Within each block type trials were averaged according to the location relative to the movement at which the DT appeared.

Data was filtered in the same way as in the previous experiments. One percent of trials were excluded due to incomplete kinematic data, 3% due to having moved the wrong hand or moved the wrong target and 4% were removed because they did not fall within 2SD of each subjects' mean RT.

4.4.3 Results

4.4.3.1 Perceptual Performance

As in Experiment 1, the most crucial factor we were interested in was whether advance knowledge of any particular component of an upcoming movement would influence the way attention was allocated. Experiment 1 failed to find any effect of block type, and attention was always allocated to the movement target, but we expected to potentially obtain different results for two main reasons:

1) The location of the DT was less predictable than in Experiment 1: the DT could appear at any of the four locations on the screen on any trial.
2) The central cues were less likely to elicit automatic shifts of attention.

We thus expected attention to be primarily allocated to the unknown component of each movement: in Target Unknown-blocks the target would receive more attention, and conversely in Hand Unknown-blocks the movement's starting point would be attended more.

Indeed, our results did differ from those obtained from Experiment 1, but in a somewhat different manner than anticipated. A 2 (block type) X 2 (relevant vs non-relevant location) X 2 (hand vs target location) repeated measures ANOVA failed to find any effects of block type ($F(1, 15) = 0.079$, $p = 0.78$, $\eta_p^2 = 0.005$), which did not interact with either relevance ($F(1,15) = 0.35$, $p = 0.56$, $\eta_p^2 = 0.023$) or whether the DT appeared at a target or hand location ($F(1,15) = 0.51$, $p = 0.49$, $\eta_p^2 = 0.033$). The type of block did not therefore influence the way attention was allocated. We also failed to find any main effects of the relevance-factor ($F(1,15) = 2.93$, $p = 0.11$, $\eta_p^2 = 0.163$).

As in Experiment 1, we did find a main effect of whether the DT appeared at a target or hand location ($F(1,15) = 41.11$, $p < 0.001$, $\eta_p^2 = 0.73$). However, as can be seen in Figure 4.12 (p. 125), the pattern had reversed since the first experiment, and more attention was being allocated to the hand-locations than to the target locations. No interactions with this factor were significant ($p > 0.48$). When controlling for multiple comparisons, a set of one-sampled

t-tests found that most locations exhibited perceptual performance better than chance, with the exception of the non-relevant target location in the target unknown-blocks ($p = 0.008$, $d = 0.76$) and relevant ($p = 0.034$, $d = 0.58$) and non-relevant target locations in the hand unknown-blocks ($p = 0.027$, $d = 0.61$) ($\alpha = 0.0063$). The key point is that while the effect of relevance is absent in Experiment 4, the effect of the hands is strong.

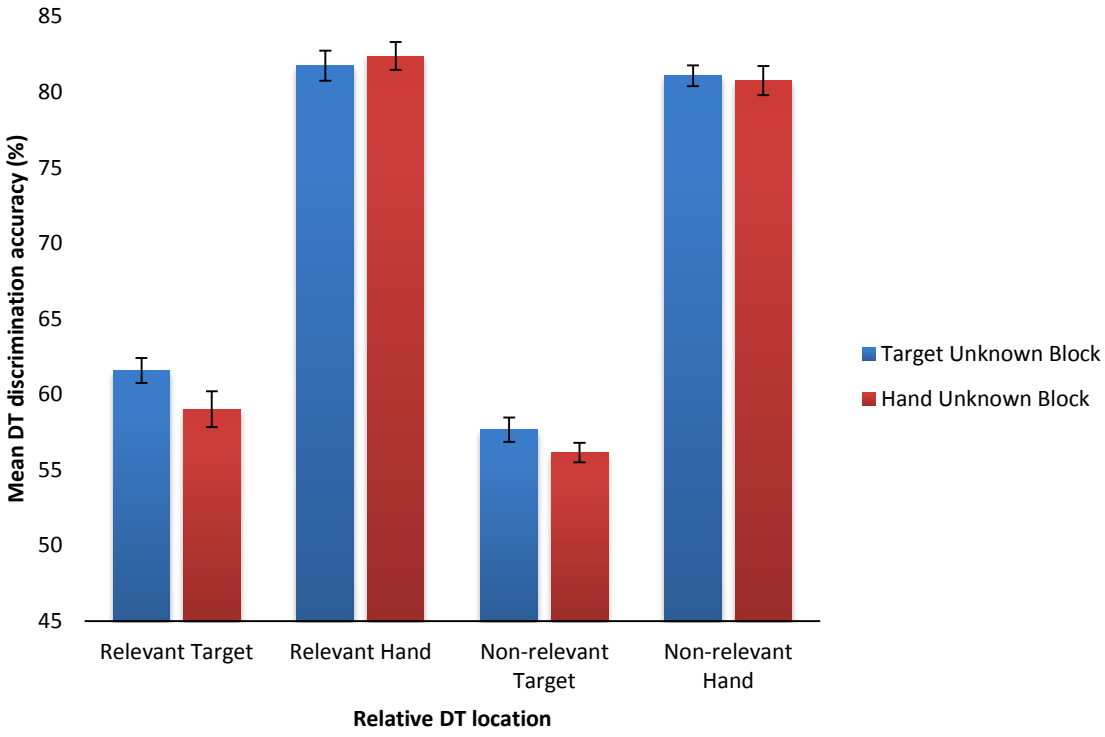

Figure 4.12. Mean DT discrimination accuracies at the four relative locations for both block types. There was no significant difference between blocks, but more attention was consistently allocated to the hand locations. Error bars represent standard errors.

4.4.3.2 Movement Performance

At first look the pattern of movement end points looks very similar to those observed in the previous experiments (Figure 4.13, p. 126). On average, the overall distance between movement end-point and the target was 16.71mm (SD = 9.05mm). The means for the different movement parameters, broken down by the different relative locations in which the DT appeared and the block type, can be seen in Table 4.4 (p. 126). The different movement parameters did not appear to be influenced by the block type or the relative location of the DT.

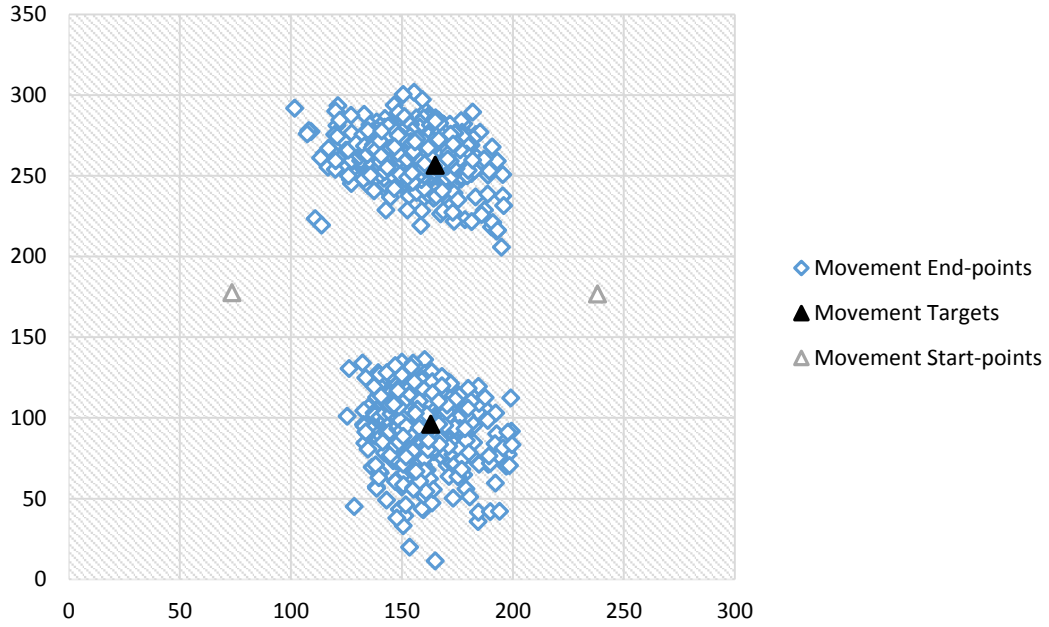

Figure 4.13. Overall movement end- and start-points and calibrated movement targets for Experiment 4.

Table 4.4. Means and SDs for the different movement parameters at the different locations, divided by block type

	Relevant Hand		Relevant Target		Non-relevant Hand		Non-relevant Target	
	M	SD	M	SD	M	SD	M	SD
				Target Unknown Blocks				
RT (ms)	478	98	474	97	473	105	479	90
MD (ms)	381	76	382	68	381	67	384	69
LA (mm)	17.1	3.25	17.5	3.38	16.5	1.81	17.3	3.36
				Hand Unknown Blocks				
RT (ms)	479	121	471	123	474	124	487	139
MD (ms)	380	71	384	69	377	73	385	72
LA (mm)	16.0	2.97	16.1	2.60	16.7	2.64	16.3	3.01

A 2 (block type) X 2 (relevant vs non-relevant) X 2 (hand vs target location) repeated measures ANOVA conducted on the LAs found no significant effect of block type on LAs ($F(1,15) = 2.67$, $p = 0.12$, $\eta_p^2 = 0.15$), which is in accordance with our findings in Experiment 1, as it also failed to find such an effect. We also failed to find a significant main effect of relevance ($F(1,15) = 0.012$, $p = 0.91$, $\eta_p^2 = 0.001$) or whether the DT appeared at a hand or target location

($F(1,15) = 1.06$, $p = 0.32$, $\eta_p^2 = 0.066$). In other words, as in Experiment 3, the LAs appeared to be unaffected the DT's location. Also none of these factors interacted with one another DT ($p > 0.15$).

A similar repeated measures ANOVA conducted on the movement RTs also failed to find a significant effect of block ($F(1,15) = 0.026$, $p = 0.87$, $\eta_p^2 = 0.002$), relevance ($F(1,15) = 0.65$, $p = 0.43$, $\eta_p^2 = 0.042$) or DT location ($F(1,15) = 0.20$, $p = 0.67$, $\eta_p^2 = 0.013$). All of these factors failed to interact significantly with one another ($p > 0.06$).

As has been the case in the three experiments preceding this one, MDs again failed to show a significant effect of either block type ($F(1,15) = 0.007$, $p = 0.94$, $\eta_p^2 < 0.001$), relevance ($F(1,15) = 0.035$, $p = 0.85$, $\eta_p^2 = 0.002$) or DT location ($F(1,15) = 2.68$, $p = 0.12$, $\eta_p^2 = 0.15$).

4.4.3.3 Additional Analyses – Hands and RTs between Experiments 3 and 4

Paired-samples t-tests once more failed to find any differences between the LAs ($t(15) = 0.34$, $p = 0.74$, $d = 0.086$) or RTs between the two hands ($t(15) = 0.088$, $p = 0.93$, $d = 0.022$).

Experiment 4 did not include mixed blocks, but if it had, they would have been procedurally identical to the early-trials used in Experiment 3. One would expect that advance knowledge of the upcoming movement (Rosenbaum, 1980) and/or having to interpret only one aspect of the central cue would result in faster RTs. An independent-samples t-test confirmed this ($t(30) = 5.06$, $p < 0.001$, $d = 1.85$) (see Figure 4.14, p. 128).

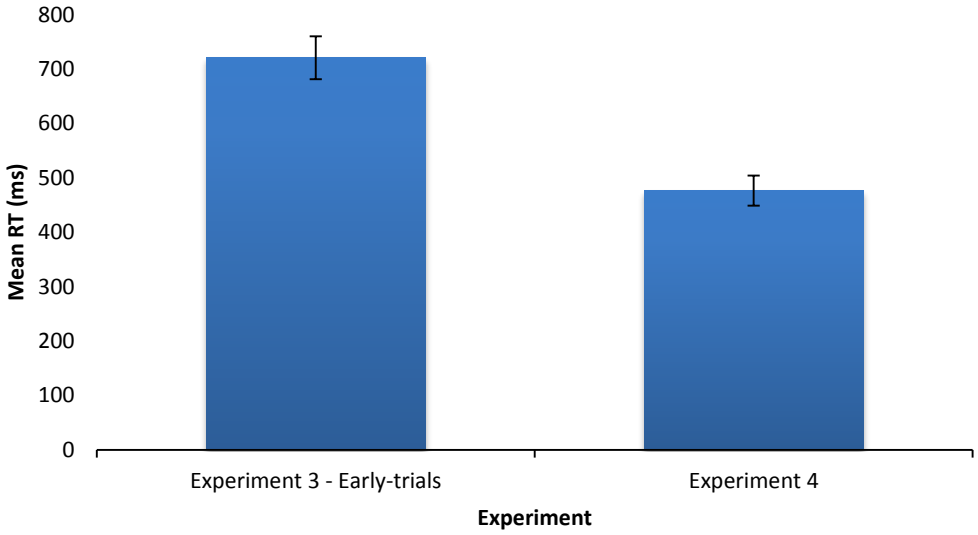

Figure 4.14. Mean RTs for the Early-trials in Experiment 3, and the overall means for Experiment 4. Subjects in the latter had significantly faster RTs. Error bars represent standard errors.

As RTs were again shorter and similar in magnitude to those seen in Experiment 1, movement onset overlapped with DT-presence in 84% of trials. Therefore we did not carry out separate analyses on trials where the DT was no longer present, as there would have been too few left to carry out sound statistical analyses.

4.4.3.4 The relevant object bias (ROB): Comparing the effect of relevance across Experiments 3 and 4

As we suggested by the RTs, the task in Experiment 4 appears to be easier to execute than that in Experiment 3. Not only do fewer features of the cue need to be processed, but with one relevant location known in advance, any attentional resources necessary for movement planning can be allocated to it earlier on, at the start of the block (Deubel & Schneider, 2003). This also reduces the number of possible movement combinations, and this makes the advanced planning of movements a more feasible strategy. These considerations may have resulted in fewer attentional resources being allocated to movement relevant locations. We were interested in quantifying the effect of relevance and assessing whether the size of its contribution was significantly different between Experiment 4 and the trials in Experiment 3

in the *early*-condition. In order to do this, we obtained a measure for the overall effect of relevance on attention which was dubbed the *relevant object bias* (ROB).

The ROB is obtained from the difference in discrimination performance between relevant trials of a certain type and non-relevant ones (e.g. discrimination performance at the relevant hand – discrimination performance at the non-relevant hand). This subtraction is carried out separately on the arcsine values of each participant, and the mean of this result yields the ROB for that condition. The overall ROB observed in a particular study can then be obtained by then averaging across conditions.

For instance, the overall ROB for the *early*-trials in Experiment 3 was obtained by first obtaining the difference between the relevant and non-relevant trials in which the DT appeared at a hand location, thus giving the effect of relevance on attention at the two hand locations. The same was then done to trials in which the DT appeared at the target locations, and the ROB was then obtained by averaging the above two values together. The process for obtaining the overall ROB for Experiment 4 was the same, except it involved also an additional intermediary stage as different ROBs for the different blocks have to be obtained first.

A paired-samples t-test found that in Experiment 4 there was no significant difference between the ROBs for the target unknown or hand unknown blocks ($t(15) = 0.59$, $p = 0.56$, $d = 0.15$). Analogously Experiment 3 found no difference in ROBs between the early or late trials in Experiment 3 ($t(15) = 1.62$, $p = 0.13$, $d = 0.40$). More crucially, an independent samples t-test found that the ROB for the *early*-trials of Experiment 3 and the overall ROB for Experiment 4 did not differ significantly from one another ($t(30) = 1.48$, $p = 0.15$, $d = 0.54$). This would suggest that although the effects of relevance were not strong enough to yield significant results, Experiment 4 might still have displayed some traces of a relevance effect. This is an intriguing possibility and would fit with the fact that performance at the target location was above chance. However so was performance at the non-target location, making this interpretation more tenuous. Nevertheless the ROB offers one a way of assessing the size of

the relevance effect also in Experiments 2 and 3. Furthermore the same technique can be used to quantify the size of the effect that the hands play in allocating attention in what can be inventively dubbed the *hand bias* (HB).

4.4.3.5 Assessing the Hand Bias (HB) and comparing ROB and HB across experiments

A measure of this *hand bias* (HB) is calculated the same way one would calculate the ROBs, except that the difference being assessed is that between trials in which the DT appeared at a hand location of particular 'relevance' and at the target location with the same relevance-status. Like for the ROBs, a paired samples t-test conducted on the HBs for the two block types in Experiment 4 found no significant difference between them ($t(15) = 0.71$, $p = 0.49$, $d = 0.18$). Furthermore the HBs for early- and late-trials in Experiment 3 also did not differ significantly from one another ($t(15) = 0.92$, $p = 0.38$, $d = 0.23$). However the overall HB of Experiment 4 was significantly higher than that of the early-trials in Experiment 3, as found by an independent t-test ($t(30) = 2.49$, $p = 0.019$, $d = 0.91$).

The existence of methodological changes across experiments makes direct comparison between them difficult, but assessing the overall size of the contribution these biases provided can be one way of doing so. They can be seen listed in the Table 4.5 below. Results for Experiment 1 are not included, as in it the DT always appeared at a relevant location.

Table 4.5. Summary of the magnitude of the ROB and HB for Experiments 2-4. This is shown both in arcsine-transformed values and in percentages.

Experiment	ROB (Arcsine)	ROB (%)	HB (Arcsine)	HB (%)	Bias Totals (Arcsine)	Bias Totals (%)
2	0.15	11.3	0.063	5.4	0.21	16.7
3	0.14	11.0	0.12	10.5	0.27	22.6
4	0.036	2.3	0.29	22.9	0.33	22.9

A pair of between subjects ANOVAs confirmed what is apparent from looking at the Table 4.5: there is a significant difference in ROB- and HB-sizes across the experiments ($F(2,45) =$

4.53, p = 0.016, $\eta^2 = 0.16$, and F(2,45) = 6.75, p = 0.003, $\eta^2 = 0.23$ respectively). Bonferroni post hoc test found that the ROB found in Experiment 2 differed significantly from that found in Experiment 4 (p = 0.031), as did the ROBs from Experiments 3 and 4 (p = 0.045). This contrasts with the non-significant difference between the ROB of the early trials in Experiment 3 and the overall ROB from Experiment 4 (p = 0.15). There was no significant difference between the ROBs from Experiments 2 and 3 (p > 0.99). With regards to the HB, its size did not differ significantly between Experiments 2 and 3 (p > 0.99) but it did differ between Experiments 2 and 4 (p = 0.003) and 3 and 4 (p = 0.039).

More interestingly, by summing the ROB and HB in each experiment, one obtains the total amount of enhancement induced by the two biases. Running a between-subjects ANOVA found no significant difference in the total attention allocated by these biases in each experiment (F(2,45) = 1.46, p = 0.24, $\eta^2 = 0.061$). In other words, although Experiments 2 and 3 only differed from Experiment 4 in terms of their ROB- and HB-sizes, the total amount of attentional enhancement provided by these biases is constant across experiments. This is consistent with the view that they are both tapping on to the same attentional resource. Which bias gets allocated more resources may depend on the features of each paradigm.

4.4.4 Discussion

Experiment 4 attempted to address for a second time the role that advance knowledge of elements of an upcoming movement had on where attention is allocated. We expected that participants in each block type would preferentially allocate attention to the unknown location. Like for Experiment 1 this was not the case, but contrary to Experiment 1, the majority of attentional resources were allocated to the hand locations rather than to the target location. The most obvious interpretation for why this was the case is that advance knowledge of an aspect of the upcoming movement made the task too easy, and thus recruited fewer resources to the relevant locations during movement preparation. In each trial participants had to only choose either only one out of two targets or one of two hands with which to execute the movement,

depending on the block-type, and there is evidence suggesting that up to two potential movements can be programmed and stored in advance (Carlsen et al., 2009). This means that participants could just select the appropriate preprogramed movement to execute, and thus the relevant locations would not need to solicit attention. This logic applies also to Experiment 1, and indeed in it the allocation of attention is also less widely distributed than in Experiments 2 and 3. It is in fact even more narrowly focused than Experiment 4, with attention being allocated only to the movement target, and this could be explained by the high likelihood with which the DT appeared there. These results would also explain why Bonfiglioli et al. (2002) failed to find enhancement at the target location of a pointing movement, as their paradigm involved pointing to either one target with one hand, or to another target with the other.

The RTs were also faster than those observed in Experiment 3. Advance knowledge of one the movement properties did thus make the movements easier to initiate, also due to easier interpretation of the central cue. This also suggests that the known relevant location will have been processed in advance.

As to why Experiment 4 showed such a large HB, this can be accounted by both the diminished ROB in that experiment, but also due to low predictability of the upcoming DT-location. As seen already in the difference between Experiments 1 and 2, when the DT location is made unpredictable, the different biases such as the ROB and HB are allowed to have a larger role in allocating the limited amount of attention available. A comparison across experiments supports this view, as the total amount of attentional enhancement provided by these biases appears to remain constant. In terms of the biased competition account (Desimone & Duncan, 1995), in Experiment 4 the HB received little competition from either the ROB or advance knowledge of the likely DT-location, and as such it managed to exert a greater influence.

4.5 Experiments 1-4: Brief Summary and Interim Discussion

The most novel finding obtained in the course of these first four experiments is discovering that attention is indeed allocated also to the starting point of a movement, above and beyond the benefits conferred by it being occupied by one's body (Experiments 2 and 3). However this novel finding was also a fragile one, and was only seen in half of the experiments. As befits a flexible and dynamic system, if the task at hand is too easy then few attentional resources are allocated to the relevant locations. Attentional biases to the body proved more robust (Experiments 2 and 4), but as was seen already at the start, both the ROB and HB can be overridden by other factors, such as advance knowledge of likely DT-location (Experiment 1). What remains striking however is how the amount of attention allocated to these two biases remained relatively constant, vindicating an account of shared VSA resources. What was also intriguing was the interplay between these two biases, and how HB may manage to influence the rate at which attention is allocated to action-relevant locations, consistent with findings by Davoli and Brockmole (2012) and Abrams et al. (2008). Further work could yield interesting insights on the specifics of the time courses involved.

Our main variable of interest in the experiments described so far and the ones to come has been their perceptual performance and the way in which it is influenced by the movements being executed. Nevertheless, we have also looked at whether movement performance was influenced by the relative location of the DT. On the whole, there is no clear evidence that this was the case. It is true that Experiments 2 and 4 respectively found either barely or almost significant interactions between relevance and locations when it came to RTs. Nevertheless when one considers the differences in the details of these interactions, their relatively high p-values and that Experiment 3 found no such significant interaction ($p = 0.29$), the data do not provide a strong case in favour of the RTs being influenced by DT location. The only reliable effect on RTs was that mixed blocks had slower RTs than target unknown or hand unknown ones in Experiments 1 and 4, but this can be attributed to slower processing of the central cue,

as in mixed blocks two features had to be interpreted instead of one. The case is even weaker when considering LAs, and especially MDs. Experiment 1 found an effect of DT location on LAs, where LAs were better when the DT appeared at the target location. Again, the p-value was relatively high ($p < 0.04$), and the subsequent experiments failed to find such an effect. Meanwhile the MDs consistently failed to show any effect of DT location. Arguably this is the variable of ours which most directly reflects movement execution, as the LAs will have depended on accurate target localisation in the movement planning stage, while RTs will be influenced by both movement planning and the time to interpret the central cue. All these results are important, as they suggest that on the whole the movement task was not specifically influenced by the perceptual task, although it is possible that there is a general dual task cost. A similar interpretation was proposed by Baldauf et al. (2006), who also found that the RTs were unaffected by the location of the DT (they did not carry such an analysis on MDs or LAs).

However another point to bear in mind is that the main task to be carried out in these experiments was a pointing action, and thus the critical spatial processing necessary as far as movement execution is concerned is to localise the target rather than identify the DT. The type of movement to be executed (i.e. pointing) will be unaffected by the actual shape of the visual stimuli at that location, as the location is the critical factor for successful movement execution. Posner et al. (1980) found that localisation of a stimulus is easier than its discrimination, and as such movement accuracies may not be as closely linked with perceptual performance as one may initially assume.

The experiments so far have had relatively long presentation times compared to some other works in the literature and fewer targets (e.g. Deubel et al., 1998; Jonikaitis & Deubel, 2011; but see Van der Stigchel & Theeuwes, 2005). This has been done in order to ensure good enough performance accuracies and in order to balance the number of movement targets and

effectors. In the next set of experiments we will be adapting our paradigm to resemble some of the other literature in terms of difficulty.

Chapter 5: The effect of increasing the difficulty on the focus of attention

5.1 Experiment 5: Increasing the difficulty

5.1.1 Introduction

One of the key take-home messages from the first four experiments is that the way in which attention is allocated to the visual environment is flexible and dependent on the task requirements. In essence we saw almost all patterns of attentional allocation possible: attention only to the movement target (Experiment 1), attention only to the two hands (Experiment 4), and attention to both (Experiment 2 and 3). When participants know with high likelihood the location at which the DT will appear, they can override attentional biases that they may have such as the ROB and HB (Experiment 1). With more unpredictable DT locations, we found that the locations relevant to the movement and the area around both hands were attended (Experiments 2 and 3). While the results of Experiment 3 suggest that allocation to the target location and to the hands occur in parallel, Experiment 4 indicates that the former stop soliciting attention when the task is too easy, such as when participants have advance knowledge of the movement they are going to execute. In this last experiment the only mechanism orienting attention in a consistent manner appears to be attention to the peripersonal space i.e. to the hands.

Our findings are consistent with those seen in previous literature. As we have seen in Chapter 1, allocation and distribution of VSA is a flexible process influenced by several different mechanisms (e.g. Desimone & Duncan, 1995), and the difficulty of the task itself can have a considerable effect and decrease the size of the spotlight (Ahissar & Hochstein, 2000). Our failure to find enhanced attentional effects at the target location in Experiment 4 may have been due to the low number of potential actions to be executed on each trial, thus allowing

participants to pre-program their movements in advance and execute them from memory (Carlsen et al., 2009; Deubel & Schneider, 2003). This may also explain why Bonfiglioli et al. (2002) failed to find perceptual enhancement at the target of a manual movement, as in their paradigm subjects also had to execute one of two actions. Furthermore, in our Experiment 4 discrimination at both hand locations was higher than at the non-relevant target location, which is consistent with the literature reviewed in Chapter 3 (e.g. Reed el at., 2006; Adam et al., 2012; Abrams et al., 2008).

A crucial element of the experiments reported thus far is that the number of possible target locations was kept down to two, so as to match the number of hand locations. We saw how altering the predictability of an upcoming movement alters the way attention is allocated, with lower attentional resources being recruited the more predictable the location. What occurs when you increase the number of possible targets? One may expect that increasing the difficulty of target selection may bias attentional allocation to the target over allocation to the two predictable hand locations, but is this indeed the case? Experiment 5 set out to investigate this. We also incorporated some improvements to the design of the experiment, which will be elucidated further below. We will once again see how the pattern of results changes in accordance to the task-parameters, and the results will set the stage for a new line of inquiry for the rest of this thesis.

5.1.1.1 Methodological changes: What and Why?

In Experiment 5, the aim was to make target selection more difficult, but also to make the task more reminiscent of some of the other experiments conducted previously, so as to better compare our results to theirs (e.g. Jonikaitis & Deubel, 2011, Baldauf et al., 2006, Deubel & Schneider 2004). The number of stimuli on the screen was increased from 4 to 8, which meant that there were 4 more possible movement targets (e.g. Baldauf & Deubel, 2008). This has the consequence that the number of possible pointing targets is not balanced out by the number of hands available to do the movement.

A further change was that we reverted to using coloured arrows to cue the movement targets, as it was believed that learning to quickly and accurately interpret an abstract symbol representing each movement location would require very large amount of practice, or otherwise be too challenging for subjects to execute a movement fast enough. Even if the participants were successfully trained to quickly interpret abstract symbols, these may also potentially have started to elicit reflexive shifts of attention.

Furthermore, in a control experiment conducted by Baldauf et al. (2006) where subjects were not to perform a movement, an arrow cue pointing at a location did not improve DT discrimination at that location. Admittedly this finding is somewhat surprising considering arrows have often been used in covert attention tasks involving no manual movements (e.g. Posner et al., 1980), and we shall revisit this finding in more detail in Chapter 7 (p. 202). However, in Experiment 1 we utilised two arrows, and if the attentional effects had been purely arrow-driven then we would have observed equally good perceptual performance at both indicated locations, which was not the case. Furthermore, the findings obtained in Experiments 2 and 3 also suggest that arrows are not necessary for a movement-relevant location to receive attentional enhancement.

For Experiment 5, the DT presentation time was decreased to 150ms. This is reduced relative to Experiments 1-4, where for the first two experiments presentation times of 400ms were chosen following piloting with 500 and 300ms. Although this is much below the time used by Van der Stigchel and Theeuwes (750ms; 2005), it is also much higher than the probe times used by Jonikaitis and Deubel (2011) or Deubel and Schneider (2004), both which used probe times of only 80ms. Baldauf et al. (2006) used a range of times (150-230ms), which were more similar to the ones utilised in the present thesis, while the seminal work conducted by Deubel and Schneider (1996) used 150ms as did Baldauf (2011) and Baldauf and Deubel (2008). We decided to use this latter presentation time, as it appeared to be in the middle of the commonly used range.

In summary, the purpose of Experiment 5 was to observe the pattern of attentional allocation in a paradigm more challenging and similar to that used in previous literature. If the motor task to be carried out in Experiment 4 was too easy to elicit perceptual enhancement at the target location, increasing the number of potential targets was predicted to re-induce attentional enhancement at the target location. The effects of this on the enhancement at the hand locations were harder to predict in advance. As evidenced by Experiment 1, allocation of attention to the starting locations is not always detectable observe. It is possible that increased difficulties in target- but not hand-selection may see the former being prioritised over the latter. The results of this experiment supported this interpretation.

5.1.2 Method

5.1.2.1 Participants

Twelve new participants (5 females, 7 males, mean age = 27.7 years, SD = 4.75) took part in Experiment 5. They all had normal or corrected-to-normal vision (though no glasses as this interfered with the eye tracking) and were right-handed by self-report. All were reimbursed £12 for their time (£6 per session). This study was approved by the Psychology Research Ethics Committee, University of Edinburgh.

5.1.2.2 General Set-up

Although the physical set-up was in many respects similar to the previous experiments, there are some crucial differences beyond the increase in the number of potential movement targets. The mirror used in the previous experiments was replaced by a two-way mirror. This allowed us to attach red LEDs to the participants' index fingers, and provide subjects visual rather than tactile feedback on their pointing accuracies, as the LEDs were visible through the mirror when switched on.

As stated above, 6 additional potential movement targets were added to the display. This resulted in the fixation cross being surrounded by 8 digital eights (1.3° x 2.0°), in a virtual

circle with a radius of 8.1°. The positions of the lower and upper target up the working surface remained the same as in the previous experiments (226mm and 383mm respectively). This time the DT was either a digital 3 or an E, and the distractors consisted of digital 2s and 5s. The black background was replaced by a grey one, so as to facilitate the eyetracking process, as this resulted in less dilated pupils which were easier to track. The stimuli, with the exception of the green or red central cue, were black on grey.

5.1.2.3 Procedure

The trial sequence can be seen in Figure 5.1 (p. 141). As in Experiments 2-4, participants were required to place their respective index fingers onto two of the digital 8s on the left and on the right of the fixation cross. At the start of the trial the LED attached to their index fingers would be on for 2 seconds to allow them to place their fingers in the middle of the two 8s on the sides. This was followed by the initial screen (580-880 ms), and then by the cue screen (250ms). The central cue this time consisted of a red or green arrow, which indicated the moving hand and target. The colour of the arrow would indicate which hand the participants would have to move, and they were instructed to point the designated *8* with the appropriate hand as quickly and accurately as possible. Participants were provided visual feedback on their pointing accuracy by the LEDs turning on 3000ms after the start of the trial. The colour cueing each hand was counterbalanced between participants.

The DT (now an 'E' or a digital 3) would appear following the cue screen at one of the 8 possible locations, while the other seven 8s would change into distractors which were either digital '2's or '5's. The DT and distractors were presented for 150ms before being replaced by 8s. Following the visual feedback on their pointing accuracy, participants were asked whether it was an *E* or a *3* that was briefly present, and their answer was keyed in by the experimenter. The DT was equally likely to appear at any of the eight locations. Testing took place in two sessions, each with a practice block of 48 trials at the beginning, followed by 3 blocks of 96

trials each, resulting in 576 trials per subject. As before, trials in which subjects broke fixation prematurely were recycled back into the trial sequence.

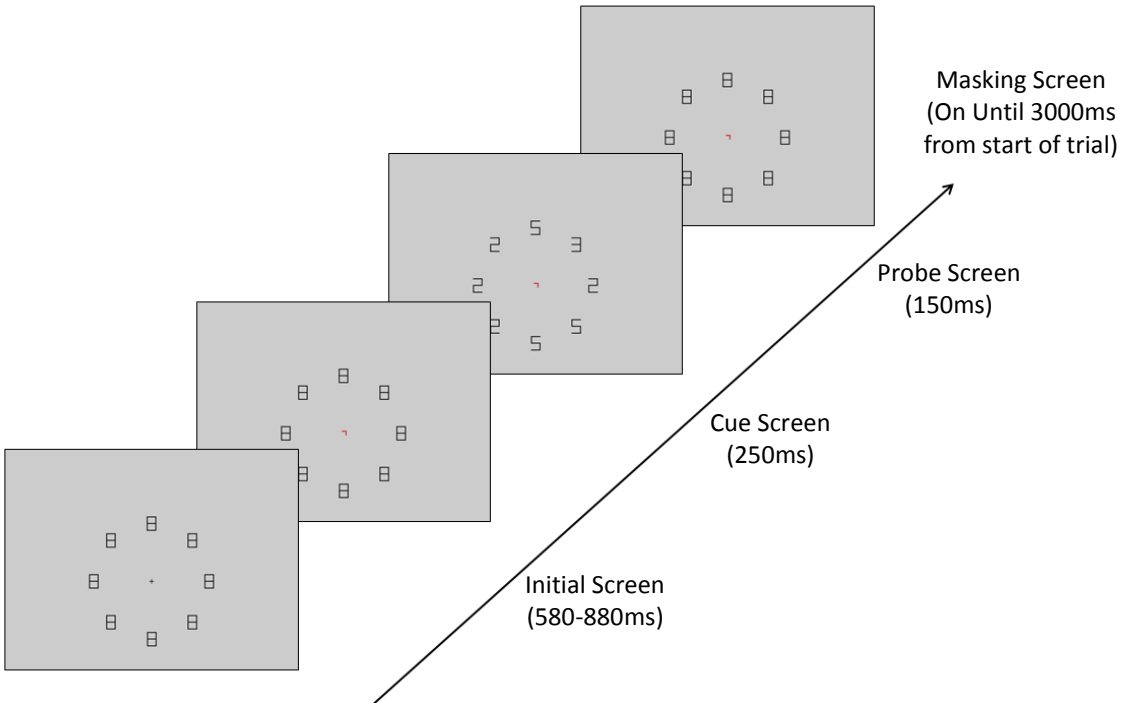

Figure 5.1. Trial Sequence for Experiment 5. See text for details.

5.1.2.4 Data Treatment

Trials were treated in the same way as in the previous experiments, and collapsed into the same categories as in Experiment 2. All trials in which the DT appeared at the movement target were collapsed together, as were trials in which the target appeared at the movement's start location, at the static hand, and the remaining non-relevant locations.

The first stage of data filtering was the same as in previous experiments. However the landing distance was calculated from pre-calibrated locations obtained separately for each participant at the start of each experimental session. As before, participants were deemed to have pointed to the target they landed closest to. One percent of the data was removed due to missing data, while 3% was removed due to an incorrect movement having been executed and 3% were removed due to RTs being 2SD above or below each participant's mean.

However, as we had increased the difficulty of the perceptual task, we only included subjects who performed significantly better than chance at at least one of the key locations (i.e. the target location, the movement's starting location, the static hand and the non-movement relevant locations), and thus removed from the perceptual analyses subjects for whom the perceptual task was too difficult. Correcting for multiple comparisons, it meant that subjects had to have discrimination performances of 69% or above at least one key location to be included in the full analyses. Only 6 of the 12 participants fulfilled this criterion and their data were fully analysed, but as we will see the pattern of results remains similar when all the participants are included in the analyses of perceptual performance.

5.1.3 Results

5.1.3.1 Perceptual Performance

The key question was what pattern on attentional enhancement we would observe in Experiment 5? Would we observe a similar pattern to those seen in several of the preceding experiments, where attention was allocated both to the movement relevant locations and to the static hand, or would the increased number of potential movement targets shift the pattern of the results? The pattern yielded by the subjects with sufficiently good perceptual performance can be seen in Figure 5.2 (p. 143).

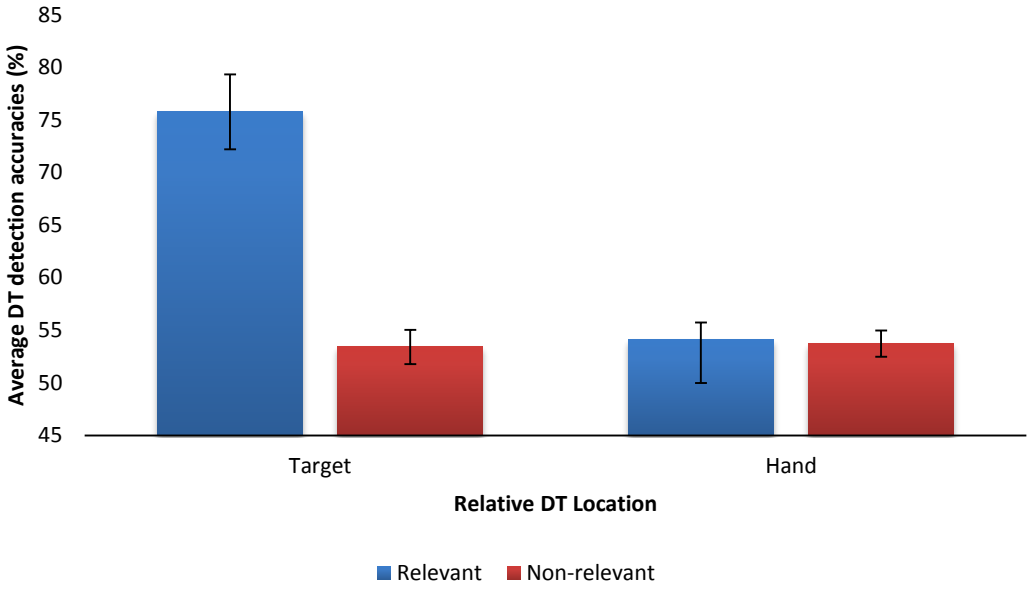

Figure 5.2. Mean DT accuracies at the different relative locations. Contrary to the previous experiments, performance was better than chance only at the movement target-location. The error bars depict standard errors.

As Figure 5.2 illustrates, participants demonstrated good perceptual performance only at the target location. A 2 (relevant vs non relevant) X 2 (hand vs target location) repeated measures ANOVA was conducted, and although this found a significant main effect of relevance ($F(1,5) = 114.70$, $p < 0.001$, $\eta_p^2 = 0.96$) and location ($F(1,5) = 13.80$, $p = 0.014$, $\eta_p^2 = 0.73$), these effects were driven by the interaction of the two factors ($F(1,5) = 17.87$, $p < 0.008$, $\eta_p^2 = 0.78$). Post hoc paired-samples t-tests found that perceptual performance between either hand locations ($t(5) = 0.18$, $p = 0.86$, $d = 0.007$), or between the movement's start point (i.e. at the relevant hand) and the non-target locations did not differ from one another ($t(5) = 0.075$, $p = 0.94$, $d = 0.031$). Furthermore, a set of one-sample t-tests found that perceptual performance at the relevant hand- ($t(5) = 1.15$, $p = 0.30$, $d = 0.47$) and at the non-relevant hand-locations ($t(5) = 2.48$, $p = 0.056$, $d = 1.01$) were not significantly better than chance. However performance at the non-relevant targets themselves was significantly better than chance (M = 53.7% SD = 2.6; $t(5) = 3.52$, $p = 0.017$, $d = 1.44$). The large effect sizes at some of the other locations suggests that a larger sample size might have revealed a wider distribution of

attention analogous to the earlier experiments. Nevertheless, VSA in Experiment 5 seems to be allocated primarily to the movement target at the expense of other locations.

ROB- and HB-measures support this conclusion. While the mean size of the ROB for the targets was 21.8% (SD = 5.22), the mean size of ROB at the starting hand was only 0.49% (SD = 7.92). As can be seen already in Figure 5.2 above, HB at the relevant location is actually negative at -21.66% (SD = 12.15), in that performance at a movement's starting point is significantly worse than at the relevant target. However there also is no trace of any HB when comparing performance at the static hand location with non-relevant targets (HB = -0.32%, SD = 5.52).

5.1.3.1.1 Perceptual performance for the excluded participants

Half of the participants were excluded because their performance did not meet the requirements for adequate perceptual discrimination. However would these participants yield results that would suggest a similar pattern of results? The answer is no, as a 2 X 2 repeated measures ANOVA found that there was no significant main effect of relevance ($F(1,5) = 1.55$, $p = 0.28$, $\eta_p^2 = 0.23$), whether the DT appeared at a hand or target location ($F(1,5) = 0.003$, $p = 0.97$, $\eta_p^2 < 0.001$) or an interaction between the two ($F(1,5) = 0.55$, $p = 0.49$, $\eta_p^2 = 0.099$). The means in for the different conditions can be seen in Table 5.1 (p. 145), as well as whether the value was significantly different from chance if multiple comparisons are not taken into account (i.e. no Bonferroni corrections were applied). Nevertheless, even without applying a Bonferroni correction, one-sampled t-tests found that DT-discrimination at none of the locations was significantly better than chance for these participants. In other words the perceptual task was too difficult for half of the participants. In the section on motor performance we shall see that this was not reflected in the motor performance.

Table 5.1. Mean DT discrimination accuracies of the excluded participants at the different locations, and whether they differed significantly from chance (without correcting for multiple comparisons). Performance at all locations was not significantly different from chance.

Location	DT discrimination accuracy (%)	SD	t-value	Different from chance? (p-value)
Relevant Target	51.41	8.81	0.41	0.70
Relevant Hand	52.78	3.37	2.01	0.10
Non-relevant Target	49.02	2.73	-1.13	0.70
Non-relevant Hand	47.88	4.55	-0.89	0.31

5.1.3.2 Movement Performance

A summary of the descriptive statistics for RT, MD and LA broken down by the DT location and whether the participant could do the perceptual task (*good perceptual performers*, GPPs) or not (*bad perceptual performers*, BPPs) can be seen in Table 5.2, while the pattern of movement end points is shown in Figure 5.3 (p. 146).

Table 5.2. Means and SDs for the different movement parameters broken down by the location in which the DT appeared for good perceptual performers (GPPs) and bad perceptual performers (BPPs). The different groups did not differ in any of their movement parameters.

	Relevant Hand		Relevant Target		Non-relevant Hand		Non-relevant Target	
	M	SD	M	SD	M	SD	M	SD
Good perceptual performers								
RT (ms)	683	155	670	157	688	166	681	156
MD (ms)	404	107	404	97	413	113	409	109
LA (mm)	16.8	3.87	17.2	4.63	16.9	5.13	17.1	4.03
Bad perceptual performers								
RT (ms)	668	107	670	102	669	111	666	104
MD (ms)	503	171	490	165	490	160	490	155
LA (mm)	15.0	2.94	16.4	3.92	15.9	3.69	15.7	3.37

An important question is whether GPPs and BPPs differ in any of the movement metrics, as this would indicate that poor perceptual performance could be linked to poorer movement planning or movement execution. For instance, it could be that BPPs were merely not paying close attention to the task, which might be reflected in movement performance. We thus conducted three mixed effect ANOVAs on the LAs, RTs and MDs, with perceptual

performance as the between groups variable (GPPs vs BPPs), and with relevance (relevant vs non-relevant) and location (hand vs target) as the within subject variables.

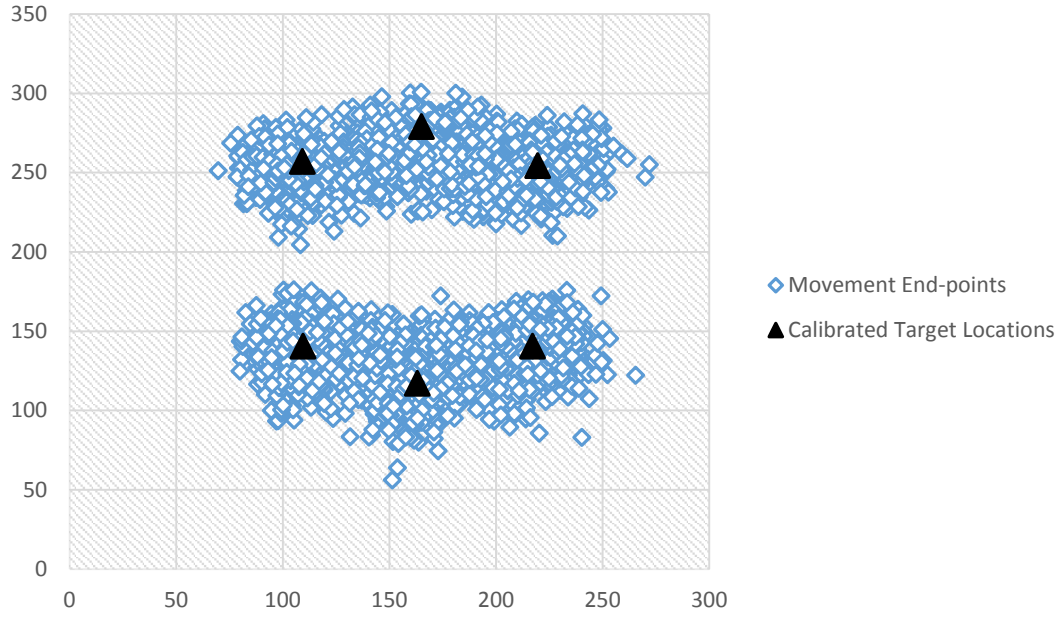

Figure 5.3. Pattern of the overall movement end-points compared to the calibrated target locations.

The analysis on the LAs revealed that the LAs between the groups did not differ significantly from one another ($F(1,10) = 0.30$, $p = 0.60$, $\eta_p^2 = 0.029$), which points to localisation of the movement target being intact in the participants of both groups. This is interesting, as one could have expected the localisation of the target to have been worse in the BPPs, but it seems that although they failed to process the movement target in sufficient detail to identify the DT when it appeared there, they did process it to a sufficient extent as to localise it as well as the GPPs. With regards to the within subject variables, there was no significant effect of relevance ($F(1,10) = 0.023$, $p = 0.88$, $\eta_p^2 = 0.002$) or location ($F(1,10) = 4.43$, $p = 0.062$, $\eta_p^2 = 0.31$). None of the interactions were significant ($p > 0.33$).

With regards to the RTs, once more there was no effect of whether a participant was grouped with good or bad perceptual performers ($F(1,10) = 0.025$, $p = 0.88$, $\eta_p^2 = 0.003$). There was again also no main effect of relevance ($F(1,10) = 0.86$, $p = 0.38$, $\eta_p^2 = 0.079$), or of location ($F(1,10) = 3.12$, $p = 0.11$, $\eta_p^2 = 0.24$). The interactions were again not significant ($p > 0.09$).

Finally, with regards to durations, the effect of group (I.e. whether they were classed as GPPs or BPPs) was once more not significant ($F(1,10) = 1.15$, $p = 0.31$, $\eta_p^2 = 0.10$). Similarly, the effect of relevance was once again not significant ($F(1,10) = 0.005$, $p = 0.95$, $\eta_p^2 = 0.27$), and neither was the effect of location ($F(1,10) = 2.83$, $p = 0.12$, $\eta_p^2 = 0.22$). The interaction between relevance, location and perceptual performance was significant ($F(1,10) = 5.25$, $p = 0.045$, $\eta_p^2 = 0.34$). This interaction is difficult to interpret, as it would suggest that for the GPPs there was no effect of the DT location when it was relevant, but when the location was non-relevant, then the durations were longer when the DT appeared at the static hand. Conversely, for BPPs, there was *no effect* of the DT location when it was *non-relevant*, but longer MDs ensued on trials where the DT appeared at the static hand. One could attempt to interpret these results to show that the execution of an action in individuals with better perceptual skills can be impaired when the DT appeared at the static hand, while people with lower perceptual acuity were more distracted by the appearance of the DT at the starting location of their movement. However the data on perceptual performance showed no evidence of perceptual enhancement beyond the movement target. Also, this is the first time in five experiments that we have found any evidence of an effect of DT-location on MDs, so what appears a more likely explanation is that this may have been a spurious finding. The interactions between location and relevance, between location and perceptual performance, or between relevance and perceptual performance were not significant ($p = 0.24$, $p = 0.39$ and $p = 0.083$ respectively).

All in all, these findings suggest that movement and discrimination accuracies are not linked to one another, as there are no difference in movement performance between GPPs and BPPs.

5.1.3.3 Additional analyses – Controlling for hand differences

Although the previous experiments have failed to find any differences between the left and right hands, it may be have been the case that increasing the number of potential targets may have made the movement task more challenging, and thus brought forward differences which were not detectable in the earlier experiments in the present thesis.

As in the previous experiments, paired-samples t-tests failed to find differences in RTs ($t(11) = 1.13$, $p = 0.28$, $d = 0.33$) or LAs ($t(11) = 1.17$, $p = 0.27$, $d = 0.34$) between the two hands. However, there was a difference in MDs, with the left hand having significantly longer MDs (M= 456ms, SD = 139) than the right hand (M = 443ms, SD = 134) ($t(11) = 2.39$, $p < 0.036$, $d = 0.69$). This may indicate that the non-dominant hand found it harder to execute movements of the same quality as the dominant hand due to the increase in potential targets (Bagesteiro & Sainburg, 2002). However, as above, since the preceding four experiments failed to find any effect of the hand used in MDs, one should avoid making too strong conclusions.

5.1.4 Discussion

Contrary to the majority of the experiments preceding it, Experiment 5 only found attentional enhancement at the movement target location. Despite the difference in the pattern of results, such as no evidence for any perceptual enhancement at either hand, these findings fit well with the framework proposed by both the first four experiments and the literature covered in the first three chapters. In essence, the results contrast neatly with those seen in Experiment 4. In Experiment 4, when the motor task was rendered too easy by advance knowledge of the upcoming movement, attentional enhancement was only found at the hand locations. Experiment 5 found the exact opposite pattern of results when the amount of uncertainty over the movement target was increased, while the effector-selection remained constant: attention was only allocated to the movement target. Attention is therefore allocated to where it is needed most, provided there are attentional resources to spare. This fits with the view of it being a dynamic and flexible system, and that the size of the different biases driving the pattern of attentional allocation depend on the task-features. An additional suggestive fact is that the advantage seen in the good performers at the movement target is similar in magnitude (21.8%) to that seen provided in total by the ROB and the HB in the previous experiments, which would be in line with the movement target benefitting from the same attentional pool as them.

Increasing the number of stimuli influencing what gets attended is not in itself a novel concept, and is the basis of the load theory of attention (Lavie, Hirst, de Fockert, & Viding, 2004; Lavie & Tsal, 1994). According to it, in conditions of *high perceptual load* (e.g. a visually more crowded screen) attention is only allocated to the most relevant stimuli, as there are not enough perceptual resources to attend to stimuli or distractors at non-relevant locations. This has the effect of rendering distractors at non-relevant locations less effective, as they are not processed in sufficient in depth for them to have an effect. Conversely, in conditions of high *cognitive* rather than perceptual load (e.g. in a working memory task), distractors are more effective as there are fewer resources available to suppress them. The aspect of load theory that is perhaps most pertinent to our current results are the effects of perceptual load. The higher number of stimuli in Experiment 5 compared to Experiment 4 increases the perceptual load participants are under, and thus perceptual resources are allocated where they are most needed (i.e. the movement target), and withdrawn from where they are not (i.e. the other locations). This account neatly explains why any HB-effects are no longer found.

The results are also consistent with our previous results in another way, which is that halving the DT-presentation time resulted in the perceptual task being too difficult for half of our participants. On the other hand, it is also true that for half of our participants the perceptual task was *not* too challenging, which starts to flag up the amount of individual variability in performance in such tasks. By the end of Experiment 8 we will see that this may be a much larger issue than is evident in the literature, and something that deserves further study. However it may explain why Van der Stigchel and Theuwees (2005) found it necessary to have the probe targets present for 750ms, Baldauf et al. (2006) between 150 and 230ms, while Jonikaitis and Deubel (2011) managed to achieve good attentional performance at presentation times as low as 80ms. Not only are the presentation times used by Jonikaitis and Deubel low, but they found good performance simultaneously at separate pointing and saccadic targets.

Perhaps more attention is available to the targets of actions than are available to one's peripersonal space?

5.1.5 A New Question: Can multiple actions recruit more attentional resources?

Experiment 5's failure to find attentional enhancement at multiple locations can be attributed to priority being given to accurate target selection over other locations, thus exhausting the available attentional resources. However, as we have already seen in sections 2.5.1. and 2.5.3 in Chapter 2, attention appears to be allocated to multiple locations in very similar paradigms when multiple actions are involved. For instance, Jonikaitis and Deubel (2011) found this when participants had to execute eye and hand movements in parallel, and their setup had an array of 12 potential movement targets on display, compared to our circular array of 8 stimuli. In the realm of movement sequences, Baldauf et al. (2006) found parallel allocation of attention to the multiple targets of a pointing sequence, again using an array of 12 stimuli, (see also Baldauf, 2011), and also found that attention was allocated to the targets of bimanual actions (2008). This latter study used an array with 8 probed locations.

Although Experiment 5 failed to find enhancement at the hand- or any other location beyond the target, the above studies suggest that having to select from multiple targets for an action does not render the allocation of attention to multiple locations impossible, at least on condition that these other locations are also the target of a movement. Somehow multiple actions may be able to recruit more VSA resources, perhaps at the expense of some other cognitive or attentional function. If that is the case, even though we did not find any HB or ROB in Experiment 5, adding an additional movement target to the task should again find attentional enhancement at multiple locations. This would demonstrate that the reason why Experiment 5 failed to find attentional enhancement beyond the target location did not stem from a general inability to attend to multiple locations. Experiment 6 was a first attempt to test this hypothesis by conceptually replicating the study by Baldauf et al. (2006). It was not the last.

5.2 Experiment 6: Do multi-step movement sequences really split VSA?

5.2.1 Introduction

The data obtained from Experiment 5 differed in two ways from the majority of the experiments that preceded it. The first one is that the perceptual task was found to be considerably harder, as evidenced by the fact that half of the participants performed the perceptual discrimination task at levels no different from chance. Another aspect that set its data apart was that it was the only other experiment in which perceptual enhancement was consistently found at only one location: the movement target. The higher difficulty in the perceptual task compared to our earlier experiments is not that surprising, as the DT presentation-time had been halved from the previous experiments to 150ms, but the tighter focus of attention is more surprising. As mentioned earlier (p. 149) it may be the case that the increased number of stimuli may have increased the perceptual load of the scene, causing attention to focus on the most relevant stimulus (Lavie & Tsal, 2004). It is possible that the movement target may have been that stimulus, as it had to be selected among a larger number of potential movement targets compared to the earlier experiments. One could argue that shortening the DT presentation times in Experiment 5 revealed that attention is allocated to the movement target first, and that this may have been the case also in the experiments preceding it, only this was hidden by the longer presentation times. However this would not fit well with previous literature (e.g. Abrams et al. 2008), or with our results from Experiment 3, which found no effect of the time course in which the DT appeared on perceptual performance.

This raises the question as to whether attention was no longer allocated to either the movement start point or to the static hand because these locations did not issue pressing enough demands for attentional resources (Desimone & Duncan, 1995), or due to more general challenges

involved in splitting of attention (Jans et al. 2010). The work of Baldauf and colleagues (Baldauf et al., 2006; Baldauf, 2011) found that for quickly executed multi-step pointing sequences, attention was allocated in parallel to two or more movement targets, with little or no cost in DT-discrimination. Baldauf and Deubel (2008) also found that attention was allocated in parallel to two target locations in bimanual movements. Taken at face value, these results suggest that the results from Experiment 5 do not reflect a general inability to allocate attention in parallel to multiple locations, merely that the movement targets were prioritised over the start point or the static hand. More crucially though, the work of Baldauf et al. (2006) found that making a two- or even three-step movement appeared to have little detrimental effects on the perceptual enhancement at the first movement target, and the subsequent movement targets received almost equal levels of perceptual enhancement. According to these results then, even though Experiment 5 failed to find attentional allocation to multiple locations, adding a subsequent movement should change this. The purpose of Experiment 6 was straightforward: have participants carry out a similar task as in Experiment 5, but replacing a single pointing movement by a two-step pointing sequence. If the findings obtained by Baldauf et al. (2006) were replicated, we should obtain improved DT-discrimination both at the first and second movement targets. This would mean that Experiment 5 did not fail to find perceptual enhancement at the hand locations simply because of general limitations in allocation of attention to multiple locations in parallel.

In order to maximise the comparability between Experiments 5 and 6, the only difference between the two was to provide participants with the instruction to conduct a second manual movement as soon as the first one was completed. This meant that there were a few notable differences between our study and that conducted by Baldauf et al. (2006). For instance, Baldauf et al.'s participants conducted all trials with their right hand, which had the fixation point as its starting position. As the mixed blocks in Experiment 1 did not produce worse perceptual performance at the movement targets than the target unknown or hand unknown

blocks, we did not expect this to be a problem. Another notable difference was that they had calibrated the perceptual task for each participant before the experimental trials. The median presentation time used by Baldauf et al. in their calibration task was 190ms, and managed to produce perceptual performances of 85% in the calibration task. We thus expected our utilisation of a 150ms presentation time to yield sufficiently good perceptual performances at the movement target(s) for at least some of our participants. There were also some slight differences in the layout of the stimuli (e.g. eccentricities were slightly larger in our layout, as were the stimuli), but nothing which would lead us to expect a different pattern of results. Furthermore, though our aim was to replicate Baldauf et al.'s results (2006), it was also important to do so within the paradigm used in Experiment 5. Contrary to our expectations, we found that the perceptual task proved too challenging for our participants.

5.2.2 Method

5.2.2.1 Participants

Twelve new participants (3 females, 9 males, mean age = 22.8 years, SD = 5.62) took part in Experiment 2. They had all normal or corrected-to-normal vision (though no glasses as this interfered with the eye tracking) and were right-handed by self-report. All were reimbursed £12 for their time (£6 per session). This study was approved by the Psychology Research Ethics Committee, University of Edinburgh.

5.2.2.2 General Set-up

The general set-up was identical to that used in Experiment 5.

5.2.2.3 Procedure

The trial sequence was the same as in the previous experiment, but participants received slightly different instructions. As before, participants had to perform a pointing movement to the target indicated by the red or green central arrow. However, in addition to this, participants then had to make a second pointing movement to the figure 8 two locations around the array

in a clockwise direction, as in Baldauf et al.'s first experiment (2006) (Figure 5.4, p. 154). Subjects were told to execute the second movement as quickly and accurately as possible following the first movement. As before, each location was equally likely to be cued, and the DT was equally likely to appear at any location previously containing a digital 8. As in the previous experiment, testing took place across two sessions, each with a practice block of 48 trials at the beginning, followed by 3 blocks of 96 trials each, resulting in 576 trials per subject. Again, trials in which subjects broke fixation prematurely were recycled back into the trial sequence.

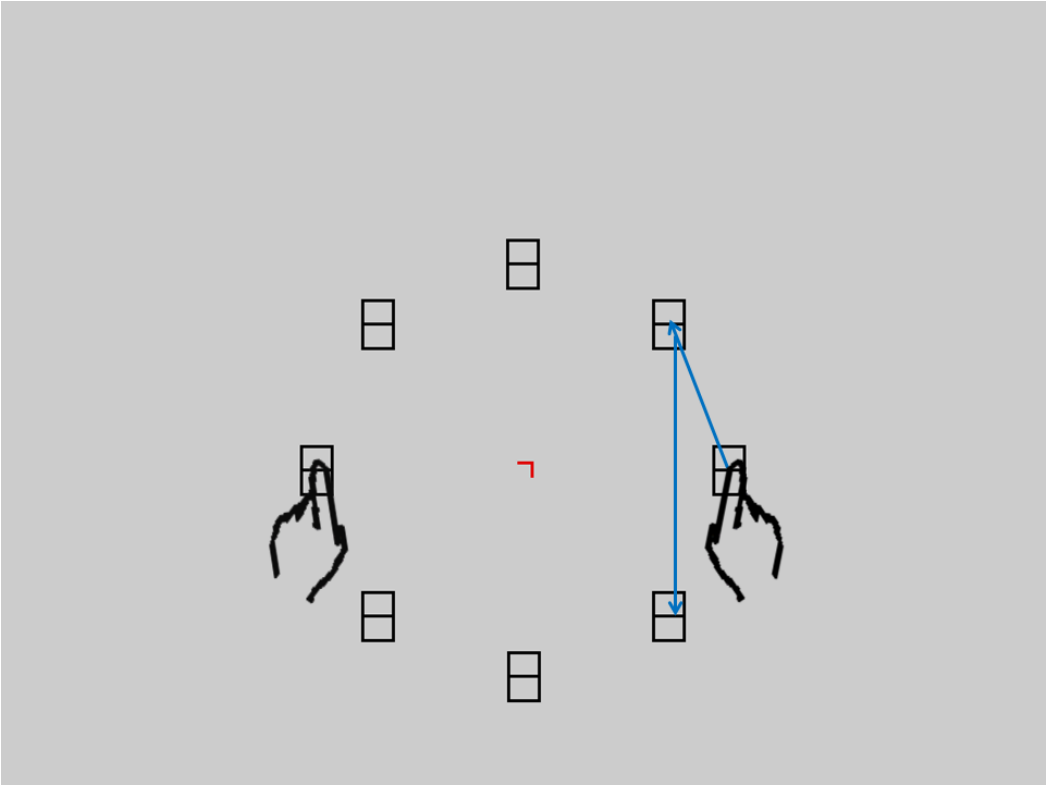

Figure 5.4. Example of the instructed pointing sequence subjects would have to do. As soon as participants had completed the pointing movement to the cued target, they then performed a pointing movement to the figure 8 two locations clockwise. Once again, participants could not see their hands.

5.2.2.4 Data Treatment

The data treatment was in many respects the same as in the previous experiments. However on some trials subjects did not slow down below 50mm/s between the first and second movements, thus making the point in which the first movement ended and the second one

started harder to ascertain. In such cases, the first movement was deemed to have stopped at the point of lowest velocity between the start of the first movement and the end of the second movement. However this behaviour may render the combined *total movement time* (TMT) of both movements a more reliable variable than the individual movement durations (Baldauf et al., 2006). This duration was the amount of time between the onset of the first movement and the offset of the second movement. We also included the measure for the time between the end of the first movement and the onset of the second one as the *between movement time* (BMT). This time was 0ms on trials in which participants did not slow down to below 50mm/s.

The data treatment was in other ways the same as the previous experiments, in that perceptual accuracies were derived by first obtaining separately the averages for the different experimental conditions for each of the two possible DTs being presented, and then arcsine-transforming them. The values obtained per condition were then averaged together. However trials were now divided into 4 conditions: whether the DT had appeared at the first movement target, the second movement target, between the two movement targets, or at a 'non-relevant' location.

The data filtering was the same as in the previous experiments. Three percent of trials were removed due to missing kinematic data, 12% due to incorrect movements (i.e. wrong movement hand or either action missing the intended target), and 4% for the manual responses being 2SDs above or below the participants' means.

5.2.3 Results

5.2.3.1 Perceptual Performance

The results obtained by Baldauf et al. (2006) would lead us to expect attentional enhancement at both the first and second movement targets. As can be seen in Figure 5.5 (p. 156), this was not the case. A repeated measures ANOVA found no significant effect of location on DT-discrimination rates ($F(3,22) = 0.34$, $p = 0.80$, $\eta_p^2 = 0.03$). Furthermore, one-sample t-tests

found that performance at none of the four locations was significantly better than chance ($p > 0.23$).

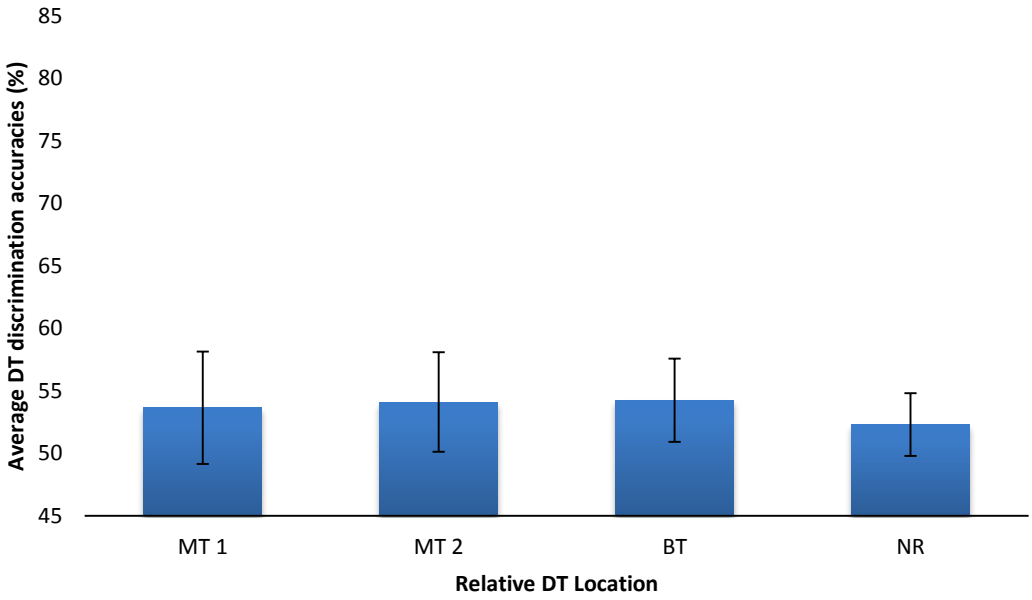

Figure 5.5. The average DT detection rates at the different relative locations (MT 1: the first movement target; MT 2: the second movement target; BT: location between the two movement targets; NR: performance at the other locations). Error bars represent standard errors.

These results could lead us to conclude either that participants are not allocating attentional resources to the different locations, or perhaps that the perceptual task was too hard for us to detect the amount of resources allocated. That is, perhaps had the perceptual task been easier, we may have observed perceptual enhancement at the movement targets. Nevertheless, the effects observed in Experiment 5 were robust enough as to be present even when the analysis was run including participants who performed at chance-levels at all locations. A closer look at the participants in Experiment 6 reveals that almost all participants performed no better than chance at *any* of the four locations. The only exception was one participant who, surprisingly, performed well at *all* locations (T1 = 95%, T2 = 92%, BT = 89% and NR = 79%). The fact there was one participant who not only performed well at the target location, but at all of them, might explain how some of the previous literature has managed to use shorter probe times, as there are people who are able to perform very well with these times provided, but they do seem to be rare. However, based both on the times used in prior literature (e.g. Deubel et al., 1998;

Jonikaitis & Deubel, 2011), and half of the participants being able to perform the perceptual task in Experiment 5, we expected a higher success rate. It bears remembering that only 12% of trials were removed because of participants had moved the incorrect hand or to the incorrect target, so they were allocating sufficient attentional resources in order to localise the correct targets on the vast majority of the trials. Experiment 5 failed to find any differences in movement performances between GPPs and BPPs, but perhaps the introduction of a second movement impaired general movement execution.

5.2.3.2 Movement Performance

Contrary to the experiments done so far, participants had to perform a two-step pointing movement, which is more complex than a single-step movement, but is this reflected in the data? Figure 5.6 (p. 158) depicts their landing accuracies. What is evident from this is how the movement accuracies had an overall wide spread, but what is less evident is how the two movements differ from one another. Differences between these for the different locations can be seen in Table 5.3 (p. 158).

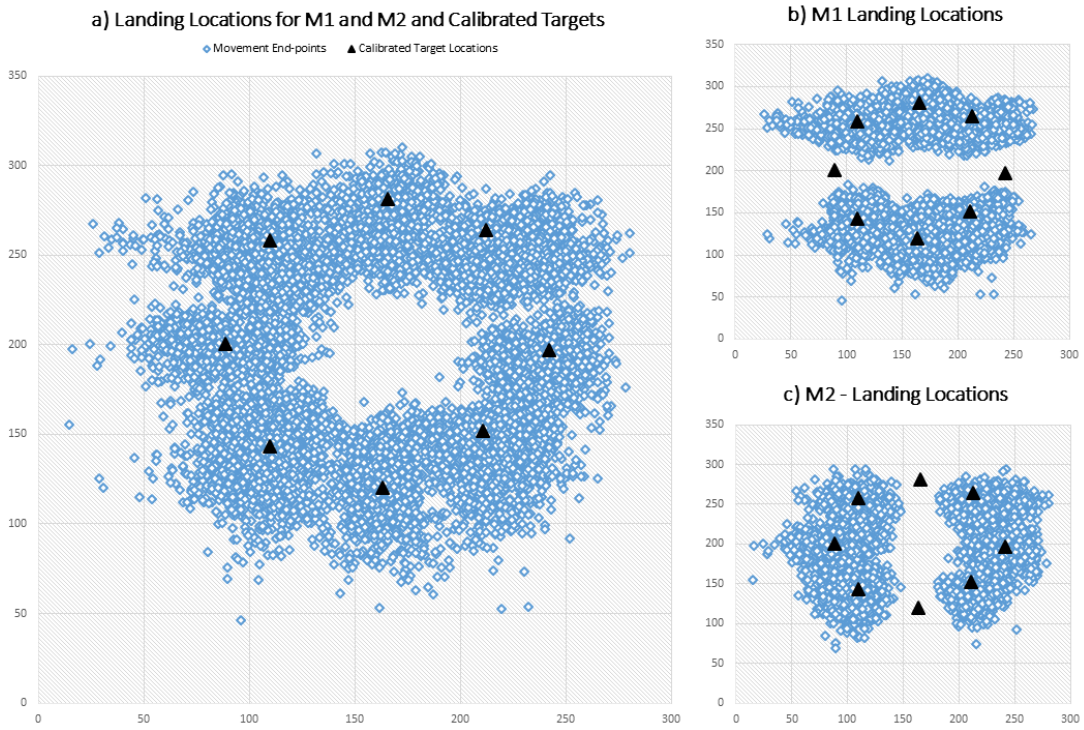

Figure 5.6. Movement end-points compared to the calibrated target location for a) movement end-points for both movements compared to the calibrated locations b) movement end-points for the first movements executed by the participants c) movement end-points for the second movements executed by the participants. N.B. The first movement target never coincided with either of the hand locations, thus resulting in different patterns for b) and c).

Table 5.3. Means and SDs for the different movement parameters for when the DT was presented at different locations. The DT location had no effect on any of the movement parameters.

	MT 1		MT 2		BT		NR	
	M	SD	M	SD	M	SD	M	SD
RT (ms)	601	42.5	310	42.3	610	45.4	607	42.5
TMT (ms)	853	182	847	179	848	176	850	179
BMT (ms)	99	67	96	69	98	68	95	66
M1 LA (mm)	20.4	3.88	20.3	3.41	21.2	4.30	20.7	3.84
M2 LA (mm)	17.5	3.73	17.6	3.32	17.2	3.71	17.6	3.34

A repeated measures ANOVA found that the location at which the DT appeared had no significant effect on the M1 LAs, ($F(3,33) = 2.50$, $p = 0.077$, $\eta_p^2 = 0.19$). A similar analysis on the M2 LAs also found non-significant results ($F(3,33) = 0.54$, $p = 0.66$, $\eta_p^2 = 0.046$).

The analyses on the RTs ($F(3,33) = 1.92$, $p = 0.15$, $\eta_p^2 = 0.15$), TMTs ($F(3,33) = 0.40$, $p = 0.75$, $\eta_p^2 = 0.035$) and BMTs ($F(3,33) = 0.38$, $p = 0.77$, $\eta_p^2 = 0.033$) all yielded non-significant results. As the DT location did not impact any of the movement parameters, it supports the

view that it went undetected, and therefore the discrimination task was too challenging for our participants.

5.2.3.3 Additional analyses – Analysing the difference between the hands and the LAs of the first and second movements

In the previous experiments we have failed to see differences between the left and right hands, but does increasing the number of movements, and thus the complexity of the task, reveal differences between the dominant (i.e. right) and non-dominant (i.e. left) hand? We conducted a set of paired-samples t-tests on the movement parameters, and though were some minor differences between the two, they again mainly did not differ from one another.

While there still were no significant differences in RTs ($t(11) = 0.51$, $p = 0.62$, $d = 0.15$), the BMTs were significantly lower ($t(11) = 2.56$, $p = 0.027$, $d = 0.74$) for the right hand (M = 91ms, SD = 64) than for the left hand (100ms, SD = 69). The shorter pause between the movements for the right hand may have been due to it being their dominant hand. However this did not translate into differences in TMTs between the two hands ($t(11) = 0.099$, $p = 0.92$, $d = 0.029$). There were no significant differences in M1 LAs ($t(11) = 0.83$, $p = 0.42$, $d = 0.24$) or M2 LAs ($t(11) = 2.04$, $p = 0.067$, $d = 0.59$).

A perhaps more interesting question is whether the LAs of the two movements differed from one another. A paired-samples t-test conducted on the overall LAs of both movements revealed that subjects were significantly less accurate in their first movements (M = 20.7mm, SD = 3.81) than their second ones (M = 17.5mm, SD = 3.40) ($t(11) = 4.61$, $p = 0.001$, $d = 1.33$). A possible explanation is that the introduction of a second pointing movement may have caused participants to rush the execution of the first movement, and thus impairing its accuracy. This interpretation is partially supported by comparing the LAs obtained in Experiment 6 with those seen in Experiment 5. Independent-samples t-tests found that the M1 LAs from Experiment 6 were also significantly worse than the general LAs seen in Experiment 5 (M = 16.4mm, SD =

3.68) ($t(22) = 2.79$, $p = 0.011$, $d = 1.19$). Meanwhile, there was no significant difference between the LAs from Experiment 5 and M2 LAs from Experiment 6 ($t(22) = 0.79$, $p = 0.44$, $d = 0.34$). While Baldauf et al. (2006) did not find that perception of the DT was impaired by the introduction of a second movement, we do seem to find that the execution of the first movement itself does suffer from it. Since Baldauf and colleagues did not report the accuracies of the first movements of their first participants, so we cannot compare these results to theirs.

5.2.4 Discussion

Contrary to our expectation, we failed to replicate the findings of Baldauf et al. (2006) or Baldauf (2011), in that we could not find evidence for attentional enhancement at the second movement target. However, perhaps more crucially, we also failed to find any evidence for perceptual enhancement at the first movement location, suggesting that the perceptual task may have been generally too challenging for our participants. There was only one participant who performed above chance at the discrimination task, and they actually performed well at all locations. The presence of one participant for whom the perceptual task was relatively easy may indicate that there are people in the population who can do the perceptual task at the required levels in such a paradigm, possibly even at the lower DT-presentation times used by previous research (e.g. Jonikaitis & Deubel, 2011). However both Experiments 5 and 6 seem to point to the fact that such individuals are rare. In the light of these findings, the relatively long presentation time (750ms) used by Van der Stigchel and Theeuwees (2005) seem less surprising.

It is worth pointing out that participants were nevertheless as accurate in their second movements as were the participants in Experiment 5, so localisation of the second movement target seemed to be unaffected by having to execute a preceding movement. Conversely, the LA to the first target was less accurate than that seen for the second target, and this may have been due participants rushing the execution of the first movement, and thus losing some movement accuracy, so as to be able to initiate the second movement. This loss in accuracy

may have gone unnoticed, as participants only obtained visual feedback on their final landing position. An additional point to bear in mind is that perhaps participants were attending more to the second movement target than to the first. However, as perceptual performance was not significantly different from chance at any of the locations, we have no evidence to support such an interpretation. Furthermore, the fact that Experiment 5 failed to find differences in LAs between GPPs and BPPs would suggest that LAs are not closely tied to perceptual performance, at least in such paradigms where the hand is not visible. It is worth noting that participants in Baldauf et al.'s 2006 study also received no feedback for their first movement, and yet their attentional performance was best at the first movement target. They did not report the landing accuracies for the first movements. We will be able to compare the LAs of GPPs and BPPs in Experiment 8 in Chapter 6 (p. 187).

Although we already saw in Experiment 5 that the perceptual task was too challenging for half of the participants, that was the case for almost all the participants in Experiment 6. A perhaps more prosaic explanation for this may be that our sample in Experiment 6 consisted primarily of BPPs, and perhaps GPPs who could have managed the discrimination task are rarer than Experiment 5 (and the previous literature) would suggest. Another explanation for this pattern of results, which does not necessarily negate the first, is that when participants have to perform a two-step pointing sequence, the priority is to allocate sufficient attentional resources to detect and localise their movement targets, and not necessarily to also discriminate them, as it is not a requirement for the movement execution itself. Perhaps attentional resources are allocated both for SfA and SfP, but although the attentional resources available may have been sufficient for the execution of a pointing sequence, the discrimination task may have required more attentional resources at the MTs than were available. In the end, for whatever reason, utilising DT presentation times of 150ms in Experiment 6 proved too challenging for 11 of our 12 participants. Experiment 7 attempted to address this by a simple measure: increasing the DT-

presentation time back to 300ms as used in Experiments 3 and 4, where perceptual enhancement had been found.

5.3 Experiment 7 – Multi-step movements with a longer presentation time

5.3.1 Introduction

Our first attempt to replicate the parallel allocation of attention during multi-step movements reported by Baldauf et al. (2006) was unsuccessful. Furthermore, subjects could not discriminate the DT even when it appeared at the first movement location. Although the reason for this is open for debate, it was clear that, for the participants taking part in Experiment 6, having the DT be present for only 150ms rendered the perceptual task too difficult. This is perhaps not surprising, considering the longer presentation times used in the first four experiments (300-400ms), and that only half of the participants were able to detect the DT in Experiment 5. However we still had expected a higher proportion of participants to be able to carry out the perceptual task, given the lower presentation times used successfully in other literature. Jonikaitis and Deubel (2011) used a presentation time as low as 80ms, and yet found that their participants could discriminate a DT at separate saccade- and pointing-targets in parallel. A possible reason as to the poorer perceptual performance observed in Experiment 6 compared to Experiment 5 is that in the former participants had to perform a two-step pointing sequence rather than pointing to a single location. This may have resulted in VSA being allocated to both locations but in insufficient amounts to result in successful DT-discrimination, due to limitations in the overall amount of attentional resources available. If this is the case, then rendering the perceptual task easier could allow us to detect any differences in perceptual enhancement across the visual landscape, and perhaps replicate the findings of Baldauf and colleagues (Baldauf, 2011; Baldauf et al., 2006). We thus implemented a simple change, and increased the DT-presentation time back to that used in

Experiments 3 and 4, up to 300ms. However, the perceptual task proved still too difficult for our participants.

5.3.2 Method

5.3.2.1 Participants

4 new participants (3 females, 1 male, mean age = 29.7 years, SD = 6.94) took part in Experiment 2. They all had normal or corrected-to-normal vision (though no glasses as this interfered with the eye tracking) and were right-handed by self-report. They all volunteered, and were not reimbursed for their time. This study was approved by the Psychology Research Ethics Committee, University of Edinburgh.

5.3.2.2 Experimental Set-up

The same set-up was used as in Experiments 5 and 6.

5.3.2.3 Procedure

The procedure was identical to the one used in Experiment 6, with two exceptions. The first was that the probe screen was on for 300ms instead of 150ms. The second was that the experiment consisted of only one experimental session of one practice block of 48 trials and three experimental blocks of 96 trials each.

5.3.2.4 Data treatment

The data treatment and filtering were the same as for Experiment 6, but with one exception. While in Experiment 6 only trials in which *both* movements landed closest to their intended targets were included in the analysis, the performance of our participants in Experiment 7 required us to somewhat relax these requirements. Although the mean LAs were comparable in magnitude the amounts seen thus far (Table 5.4), participants landed their pointing movements closest to *both* the intended targets on only 59.6% of trials. However, participants were landing accurately to the first target on 75.3% of the trials, and closest to the second

target on a very similar 74.4% of trials. Due to this, the number of trials in which the participant landed closest to at least one of the indicated targets was 90.2%. One has to bear in mind that the second movement target was contingent on the first target having been accurately selected, so if people were pointing to the correct location at the end of the second movement, then they will have intended to point to the correct first movement target.

It may be that the relatively poorer performance can be attributed both to the smaller sample size used in the present experiment, as well as fewer trials, thus giving participants less time to improve their pointing accuracies. Furthermore, we have seen in the several diagrams depicting the movement end-points that the different movements do not have compact landing accuracies, so a correctly intended movement being incorrectly aimed is far from implausible.

This led to 2.3% of trials being removed due to incomplete kinematic data, 13.6% being removed due to incorrectly aimed movements, and 4.7% due to too fast or slow RTs.

5.3.3 Results

5.3.3.1 Perceptual Performance

The main objective of Experiment 7 was to render the perceptual task easier by increasing the probe presentation times up to 300ms and thus increase perceptual performance to levels above chance. If this was successful, then the question was to attempt to address whether we would replicate the pattern of findings reported by Baldauf et al. (2006), who found attentional enhancement at both movement targets. As can be clearly seen from Figure 5.7 (p. 165), our efforts proved yet again unsuccessful.

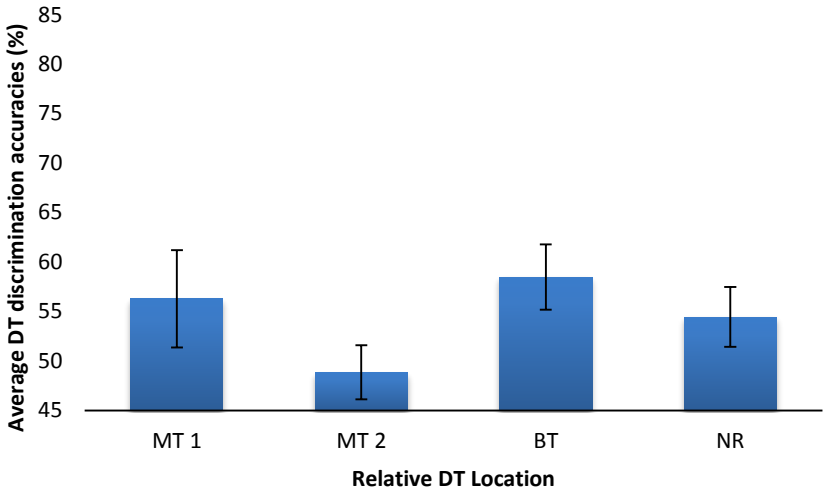

Figure 5.7. The average DT discrimination rates at the different relevant locations. As in Experiment 6, even with presentation times twice as long, perceptual performance at none of the locations differed significantly from chance.

A repeated measures ANOVA ran on the four relative DT-locations once again failed to find any differences in perceptual accuracy between them ($F(3,9) = 2.11$, $p = 0.17$, $\eta_p^2 = 0.41$). Furthermore, performance at none of the locations was significantly different from chance (MT 1: $p = 0.28$; MT 2: $p = 0.71$; BT = 0.093; NR: $p = 0.25$). Experiment 7 thus once again failed to find evidence of perceptual enhancement at the different movement targets, or at any of the other locations for that matter. Is the movement performance also similar to that seen before?

5.3.3.2 Movement Performance

As alluded to in this experiment's Data Treatment-section, trials in which participants landed closest to the intended targets for both movements were rarer than in Experiment 6. The overall pattern of the landing locations can be seen in Figure 5.8 (p. 166), while a more detailed breakdown for the different movement parameters can be seen in Table 5.4 (p.166).

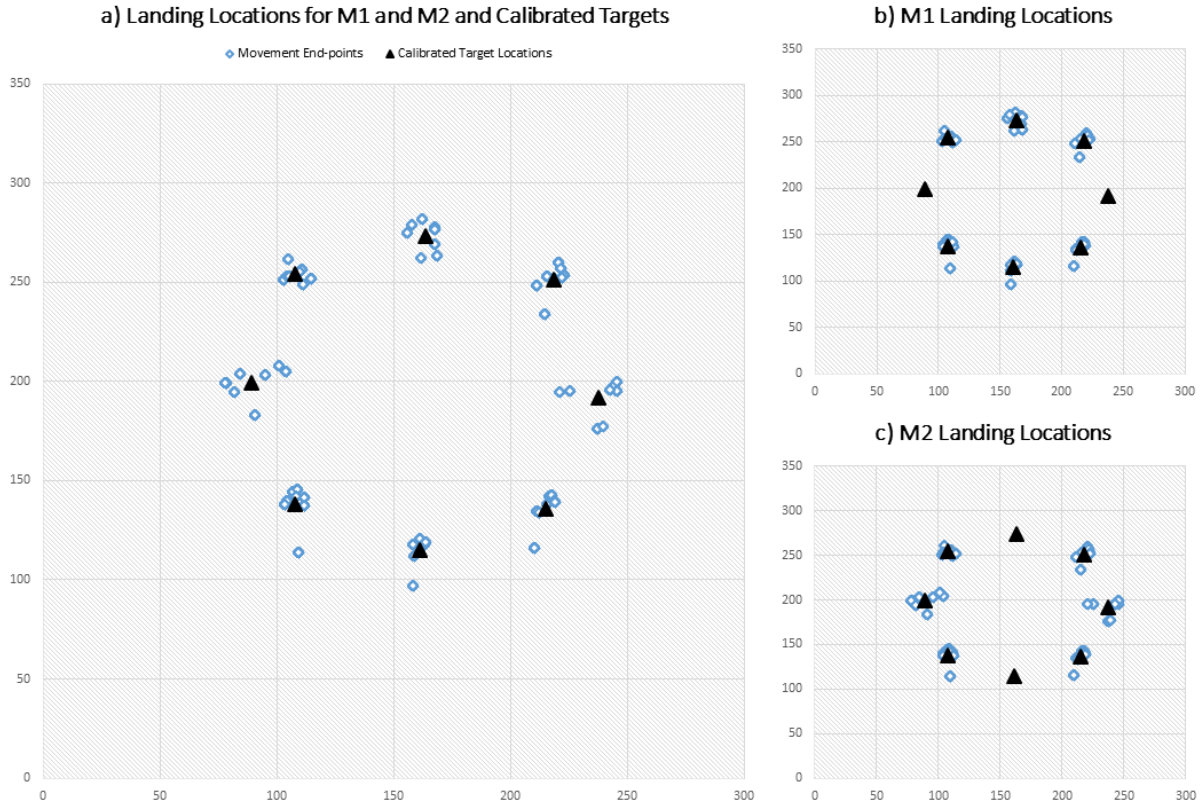

Figure 5.8. Overall pattern of the movement end-points for the different targets. NB. Not all end-points are displayed.

Table 5.4. Means and SDs for the different movement parameters for when the DT was presented at different locations. As in Experiment 6, the DT location had no effect on any of the movement parameters.

	MT 1		MT 2		BT		NR	
	M	SD	M	SD	M	SD	M	SD
RT (ms)	725	103	724	113	726	86.3	740	121
TMT (ms)	920	142	920	118	901	111	912	111
BMT (ms)	126	10	131	77	128	70	127	75
M1 LA (mm)	22.2	4.71	23.4	3.27	24.9	5.29	23.5	3.43
M2 LA (mm)	20.9	3.73	22.1	4.93	23.7	4.76	22.4	2.99

A set of repeated measures ANOVAs found that for all movement parameters, the location relative to the movement at which the DT appeared had no effect. This was the case for the RTs ($F(3,9) = 0.69$, $p = 0.58$, $\eta_p^2 = 0.19$), TMTs ($F(3,9) = 1.06$, $p = 0.41$, $\eta_p^2 = 0.26$), BMTs ($F(3,9) = 0.12$, $p = 0.95$, $\eta_p^2 = 0.039$), M1 LAs ($F(3,9) = 1.74$, $p = 0.23$, $\eta_p^2 = 0.37$) and M2 LAs ($F(3,9) = 1.57$, $p = 0.26$, $\eta_p^2 = 0.34$). As for Experiment 6, this is consistent with the poor

perceptual performance of our participants, and them finding the discrimination task too challenging.

5.3.3.3 Additional Analyses – Comparing hands and LAs

A paired-samples t-test was conducted on the RTs which found that the left hand (M = 728ms, SD = 113) was significantly faster than the right (M = 739ms, SD = 115; t(3) = 6.73, p = 0.007, d = 3.37). This contrasts with Experiment 6, which found no differences between the two hands. There is previous research suggesting that under the right circumstances right handers do have faster RTs with their left hand (e.g. Verfaellie & Heilman, 1990), but we have not seen this effect replicated in our other experiments so far. Furthermore, since the two latest experiments only differed in DT-presentation time, but the earlier one had a sample three times the size, these results should be taken with some caution regarding their generalisability. Additional paired-samples t-tests found that the TMTs (t(3) = 0.016, p = 0.99, d = 0.008) and BMTs (t(3) = 0.59, p = 0.60, d = 0.30) also did not differ between hands. The same was the case for LAs, where neither hand differed from one another: this was the case for both to the first (Left Hand: M = 22.6mm, SD = 6.20; Right Hand: M = 24.1mm SD = 5.88; t(3) = 0.31, p = 0.78, d = 0.16) and the second movements (Left Hand: M = 20.1mm, SD = 3.33; Right Hand: M = 24.3mm, SD = 4.93; t(3) = 1.67, p = 0.19, d = 0.84). However the large effect size for the second movement suggests that failure to find the difference between the two hands could be attributed to too small a sample.

In Experiment 6 we saw that people were overall more accurate with their second movements than with their first ones. The LAs for the first movement were again less accurate than for the second (LA1 M = 23.5mm, SD = 3.71 vs LA2 M = 22.3mm, SD = 3.42), but a paired-samples t-test showed this difference was not significant (t(3) = 1.81, p = 0.17, d = 0.91). As suggested by the large effect size, this may have been brought about both by the fewer trials in the present experiment, but also due to the smaller sample size, which may render this result less reliable than those obtained in Experiment 6. However as this was not the central purpose of the

experiment, and due to the difference in sample sizes and trial numbers between the experiments, we did not investigate this discrepancy between Experiment 6 and 7 further.

5.3.4 Discussion

The main goal of Experiment 7 was simple: to repeat Experiment 6 but with an easier perceptual task and thus attempt to uncover traces of perceptual enhancement which may have been too small to be detected in the previous experiment. This was done by doubling the DT-presentation times to 300ms, a presentation time which proved successful in Experiments 3 and 4. However, we once again failed to find perceptual facilitation at either movement target location. Many of the points raised in the previous discussion section are still valid, but it is worth briefly re-iterating some of the possible reasons why we still failed to detect any perceptual enhancement, even when using longer probe times.

The first key point to remember is that although the DT-presentation time had been increased to the times used in some of the preceding experiments, the perceptual load has also increased, due to the higher number of potential targets/stimuli on the screen (Lavie, 2010; Macdonald & Lavie, 2008). For instance, Macdonald and Lavie (2008) consistently found that detection of a task-irrelevant stimulus decreased with an increase of perceptual load. It is also worth remembering the results of Ahissar and Hochstein (2000), who found that the spread of attention becomes narrower with increased task difficulty (p. 22). Furthermore, we already saw in the work of Awh and Pashler (2000) that the introduction of more stimuli leads to inhibition of non-pertinent ones (p. 26), where attentional inhibition is more than the absence of attentional enhancement at a specific location (Wühr & Frings, 2008). A related point is that the introduction of multiple foci of attention may dilute the strength of each attentional peak as pointed out even by Baldauf and Deubel (2010). As proposed earlier in the present thesis (e.g. p. 14), this may result in sufficient attentional levels for detection but not discrimination.

A final point worth re-stating revolves around individual differences. It bears remembering that the presentation time used for the DT in the first two experiments was 400ms, as previous piloting had found that lower times could produce insufficiently good perceptual performance. Latter experiments (3 and 4) did find better-than-chance perceptual discrimination at 300ms, but this fluctuation in performance indicates that there is considerable individual variability. Although there are some experiments that use a *staircase procedure* (i.e. increasing or decreasing the task difficulty depending on the accuracy of the participants' responses) to calibrate the task difficulty for each individual and keeping it constant throughout the task (Castet et al., 2006; Festman et al., 2013a, 2013b; Montagnini & Castet, 2007), several experiments do not make any mention of individual differences in performance. A notable example is the seminal paper by Deubel et al., (1998) which first found attentional enhancement at a pointing target and presented their DTs for 150ms, as well as the work by Jonikaitis and Deubel (2011) who found parallel attentional enhancement at the saccade and pointing targets using presentation times as low as 80ms. Neither of these studies provided information on how the presentation times were selected, how much individual variability there was, or any details regarding recruitment of participants. Recycling of participants may lead experimenters to inadvertently overgeneralise from their results to the population. This issue could be additionally conflated by the usually small sample sizes used in this literature (e.g. Deubel et al., 1998: 5 participants; Baldauf et al., 2006: 6 participants; Kowler et al., 1995: 2 participants). Though small samples are not automatically a problem, this may cast doubt on the generalisability of these results, and shed light as to why the work by Baldauf et al. (2006) has proven difficult to replicate in the present thesis.

Although Baldauf et al. (2006) did not use a staircase procedure or a particularly large sample size, they did attempt to take individual differences into account by having each participant carry out a pre-testing session in order to calibrate the length of the presentation time needed for each participant to perform sufficiently well in the perceptual task. Over the course of the

experiments within this chapter we have had difficulty in finding participants who could perform the perceptual task, and perhaps calibrating it in a similar fashion as Baldauf et al. (2006) might finally yield the results we have failed to replicate thus far. For this reason our final experiment incorporated such a calibration of the perceptual task by means of a pre-test session.

5.3.5 Experiments 5-7: Interim Discussion and Summary

The last three experiments have had a two-fold focus. In Experiment 5 we attempted to expand on the results obtained in the first four experiments in a paradigm with more visual stimuli and shorter DT presentation times. When we found perceptual enhancement only at the movement target, we attempted to see whether this was due to a general inability to allocate attention to multiple locations in a paradigm with higher perceptual load (Lavie, 1995, 2005), or whether two-step movements could be used to elicit perceptual enhancement at multiple relevant locations (Baldauf et al., 2006; Baldauf, 2011). To our surprise, these last two experiments failed to find attentional enhancement at *either* movement target, even when the DT was presented for 300ms. *All* the participants appeared to find the perceptual task too challenging, although their motor performance was comparable in accuracy to the experiments conducted so far, with the exception of the LAs for the first movements in Experiment 6. This suggests that SfA may have been still as effective as before, and the attentional resources were sufficient to ensure accurate SfA when a second movement is added. However, more attentional resources may have been necessary for the successful completion for SfP than were available, which led to poor DT-discrimination rates. Our results highlight the importance of not automatically equating the task demands of perception and action. After all, in our experiments successful action execution is never dependent on successful identification of the DT. We will revisit this issue following the final experiment, but to all this one also has to add the possible attentional costs induced by higher perceptual load (MacDonald & Lavie, 2008).

The fact that only half of the participants in Experiment 5 could discriminate the DT at the movement location at levels above chance also highlights the amount of variability in perceptual performance between participants. Although not all studies report their participant selection criteria or how they came to use the probe times they did, individual differences may also account for why some studies found good perceptual discrimination accuracies at movement-locations even when using displays with higher perceptual load. For instance, it may simply be the case that participants who took part in the study of Deubel et al. (1998) among others, simply happened to have had better perceptual acuity than most of the participants who took part in these experiments. Alternatively, another speculative explanation is also that not all of the participants were previously unknown to the experimenters, and been trained by taking part in previous experiments, or otherwise consistently produce a certain pattern in the data which may not reflect the behaviour of the general population. We proceeded to conduct one more experiment to explore these questions further.

Chapter 6: Calibrated discrimination

6.1 Experiment 8: Multi-step movements with calibrated presentation times

6.1.1 Introduction

This is the last empirical chapter in the present thesis, in which we attempt one more time to replicate the results obtained by Baldauf et al. (2006). The results from their five experiments very consistently found perceptual enhancement at multiple locations. Before proceeding further and trying to untangle what may be at the root of the discrepancy between our results and theirs, a closer look at their experiments is in order.

6.1.1.1 A closer look at experiments done by Baldauf, Wolf and Deubel (2006)

Baldauf et al. (2006) carried out 5 experiments, all of which consistently found perceptual enhancement at two or more locations in parallel when these were part of a multi-step pointing sequence. Their first experiment consisted of subjects being presented with a circular array with 12 figure 8s around fixation. Subjects had to point to the centrally cued target, and as soon as this first movement was completed they performed an additional pointing motion from their landing location to the figure 8 two locations clockwise in the circle. Additionally, subjects had to discriminate which of two DTs had briefly appeared in one of the locations. How long the DT was presented for was calibrated separately for each participant. This calibration was achieved in a pre-test session, where subjects had to perform a single pointing movement to a target, and the DT was always presented at the movement target location, for differing amounts of time. Based on the discrimination accuracy performance in the pre-test session, the DT-presentation time was set so as to produce an estimated 85% accuracy. The probe presentation times used per participant in the experimental part ranged between 150 and 230ms (M = 190ms).

Their first experiment, conducted on 6 participants, found that participants had mean discrimination accuracies of 86% when the DT appeared at the first movement location. This high level of performance was to be expected from prior literature (e.g. Deubel et al., 1998) and performance levels at the pre-test session. However discrimination performance at the second movement target location was also high at 75%, and the discrimination performance at the two movement targets did not differ significantly from one another, although only just ($p < 0.063$). Detection performance of probes in the intermediate location between the two movement targets (54%), or at movement-irrelevant locations (56%) was not significantly different from chance. The key points of these findings are that not only is attention apparently allocated in parallel to two non-contiguous locations, but also that little or no cost is associated with this with regards to perceptual performance at the first movement target. Perceptual performance at the first movement target is not impaired by the presence of a second movement target, and DT-discrimination at this second location is not significantly worse than at the first. It is also worth noting that Baldauf et al. (2006) conducted a separate control experiment with separate participants, which had the same procedure but with the exception that participants were to keep their finger static throughout it. This was conducted in order to test whether participants would allocate attention to where the central cue was pointing. They found that the arrow alone in the absence of any movement did not elicit shifts of attention. It bears pointing out though that we do not know if and how they calibrated the DT-presentation time for these 'static' participants, so we do not know whether the task might just have been too hard for them to perceive any stimuli, as was the case in our preceding experiments.

It is possible that the attentional paradigm in their first experiment was not taxing enough to elicit a drop in perceptual performance, so in their second and third experiments Baldauf et al. increased the pointing sequence from two movements to three. In their second experiment, 5 of the participants from the first experiment now performed a third pointing movement to a target which was another 2 locations clockwise in the stimulus arrangement in respect to the

second movement target. The perceptual performance at the first movement target was remarkably similar to that in Experiment 1 (85%), and the performance level at the second movement target was again not significantly worse (75%; $p > 0.057$). However, somewhat surprisingly perceptual performance at the third movement target was as good as at the second movement location (74%, $p > 0.52$), although significantly worse than at the first movement location ($p < 0.029$). Baldauf et al. (2006) aptly describe the finding that all three locations are attended already before movement onset as "quite amazing" (p.4364).

In their third experiment Baldauf et al. (2006) were back to testing 6 participants, with the sixth one having taken part in their Experiment 1. Here the third pointing movement target was the figure 8 directly opposite to the second movement target. This was done in an attempt to make the movement combination more complicated, as they hypothesised that perhaps the good performance of their participants may eventually create a mental template for the move that they are about to carry out. The pattern of results of this latter experiment did not differ from the previous one, with discrimination accuracies of 88%, 79% and 70% at the first, second and third movement targets respectively. Although participants are reported to have stated that the experimental task in their Experiment 3 was more difficult and required more effort to perform (at least in early practice), this was not evidenced by the movement data, with movements being as accurate as before. It is therefore debatable whether this third experiment solves the issue of a template for attentional allocation being created, and whether the movement sequence was actually more complicated than the previous one. Furthermore, if participants could form a template for the movement sequence in Baldauf et al.'s Experiment 2, there does not seem to be an inherent reason why they could not do the same in Experiment 3. It is true that the third movements had a larger amplitude in the latter experiment, and the increased muscle exertion might have been the cause for the reported increase in difficulty.

In order to attempt to tackle training effects or any particular strategies being deployed, in their Experiment 4 whether a single-, double-, or triple-pointing movement had to be executed

changed between trials, and was indicated by a Roman numeral at the start of each one (I, II and III respectively). The participants were the same that took part in Experiments 1 and 3, and the triple movement was the same one as the one executed in Experiment 2. The results obtained in Experiment 4 were clear: DT discrimination was enhanced only at the pointing targets in that particular trial. For instance on trials where subjects had to perform a single pointing motion, the DT-discrimination performance did not increase at the locations which would have been the targets of a second or third movement targets if the trial type had been different.

This fourth experiment addressed the question as to whether attention was being allocated strategically in a spatial template, and the results indicated that an action needed to be directed to a specific location for it to receive additional attentional resources, at least in the present experimental paradigm. How successfully it addressed training effects is another matter. Subjects may not have been allocating attention reflexively to different locations in absence of a movement to them, but this does not mean that the amount of attention allocated to the different components of a multi-step movement itself was not increasing. A better way to address training effects would have been to use new participants. This would have required a new calibration session, but unless subjects were difficult to come by who can perform the task, it should not have been prohibitively resource-consuming.

A question which remains is whether attention is being allocated serially or in parallel to these multiple locations. Baldauf et al. carried out a fifth experiment in an attempt to answer this question. Subjects again were to perform a two-step pointing movement, but this time they were presented with two DTs instead of one, and instead of reporting their identity, they had to report whether these two were the same or different. This meant that subjects had to attend both locations simultaneously to succeed. They made a few other changes to the paradigm, the main one being that the presentation time was decreased to 60ms, so as to minimise the likelihood for serial shifts of attention. In order to compensate for this increase in difficulty,

they decreased the number of stimuli on screen from 12 to 4, into an arrangement similar to the one we had in our Experiment 1 (a similar approach was used by Godijn and Theeuwes (2003)). Five out of the 6 subjects had already taken part in Experiments 1-4.

Consistent with the previous findings, subjects were found to provide more correct responses when the DTs appeared at the two movement targets (69%) than when only one of them (58%) or neither one did (57%). Although the overall perceptual performance appears to be lower than in the previous experiments, this apparent discrepancy can be accounted for when calculating the expected performance based on the first experiment. This was calculated by adding together the probabilities of correctly identifying the DT at the first target and of incorrectly identifying *both* DTs. This is done by using the following formula, $p_1 * p_2 + (1 - p_1) * (1 - p_2)$, where p_1 and p_2 were the probability of identifying the correct DT at the first and second movement targets respectively. Since the discrimination rates at the first and second movement targets in their first experiment were 86% and 75% respectively, the expected accuracy would have been 68%, which is only 1% below what was observed.

Nevertheless it is surprising that by decreasing the DT-presentation times down to 60ms, subjects were performing as well as one would have expected if they were as good as in their first experiment. It would have been interesting to see whether subjects would have now performed better if they repeated their pre-test session from their first experiment. It is possible that after taking part in 5 experiments subjects had improved in their VSA orienting and as such they may be able to execute the task faster, as seen with Czerwinski et al. (1992). Baldauf et al. conducted no analyses into any such potential training effects. One has to remember though that not only were the presentation times decreased, but also the number of stimuli. This makes direct comparison to the previous experiments difficult for reason which we will be discussing in the next section, together with other potential issues.

6.1.1.2 Baldauf et al.'s results: robust but problematic

These results are remarkably consistent and the several control experiments address many issues one may have wanted to raise. Furthermore, the ease with which attention appears to be allocated to multiple movement targets is surprising when one considers that attention is often considered a limited resource. As we saw throughout Chapter 2, attention and movement are closely coupled (especially attention and saccades), and it may be that action planning is a special case in which extra attentional resources can be allocated in order to attend multiple locations in parallel, perhaps resulting in a cost in another form of attention. However our experiments carried out so far tell a different story, in which under the correct circumstances attention may be allocated to multiple locations, but this effect is fragile and hard to pin down. Our last two experiments in which we first attempted to replicate the results obtained by Baldauf et al. failed to find attentional enhancement at *any* location. There are some issues in the methodology used by Baldauf et al. (2006) which may help to account for these differences. We have alluded to some of them already, but the key ones bear re-stating.

One of the first issues concern the participants. It bears noting that their sample size was fairly small, with only 5 or 6 participants in each experiment, and that they used the same participants in all experiments. Using small sample sizes is only appropriate in research where the effects are large, robust, and consistently observed across all individuals. The results of Baldauf and colleagues are somewhat surprising, and one could be more confident that these results would generalise if the same participants were not being used across the different experiments. A sample size of six individuals implies a robust finding of almost universal applicability. Using the same participants has the effect of undermining how generalisable these results are across the population, as there may have been a selection bias when participants were recruited. A second issue that arises from Baldauf et al. (2006) using the same participants is that this may have resulted in practice effects across the experiments, which got progressively more challenging. Furthermore, in Baldauf et al.'s first experiment participants had to undergo 3

practice blocks of 96 trials each, before conducting 4 experimental blocks of 96 trials. This is considerable amount of practice, and certainly not a prerequisite for participants being able to understand what was requested of them. It may therefore be the case that the apparent splitting of attention may only emerge with time, after a large amount of practice. Practice may also increase the speed of orienting of attention, and thus produce something that looks like parallel allocation of attention but in reality results from quickly executed serial shifts (Czerwinskiet al., 1992; Jans et al., 2010). This may have accounted for the results in their fifth experiment, where the DT discrimination performance was high despite presentation times a down to on average a third of the length of those used in the previous ones (60ms vs 190ms).

As we alluded to at the end of the previous section, Baldauf et al.'s decreasing of the number of stimuli in their fifth experiment is also problematic, and may also explain how participants performed better at lower presentation times which do not have to do solely with making the discrimination task easier. As we covered in Chapter 1, Awh and Pashler (2000) found evidence for the splitting of the attentional spotlight when there were many stimuli being presented on the screen, with processing of distractors between cued targets being inhibited (p. 26). However when these distractors were removed, then participants switched to a unified focus of attention to process both targets, as evidenced by an increase in performance at uncued locations. What this implies is that the removal of stimuli in Baldauf et al.'s fifth experiment participants may have allowed participants to deploy a single focus of attention, which may have encompassed both locations. In this respect the processing of both movement targets would indeed have been parallel, but due to the increase of the size of the attentional spotlight rather than due to the execution multi-step pointing. Due to the differences in the stimulus-layout, their final experiment cannot be taken as direct evidence of attention having been allocated in parallel in their previous experiments.

There are however more prosaic explanations as to why we may have failed to replicate the results of Baldauf and colleagues (2006) (see also section 5.2.1, p. 152). The first one is that

in order to be able to make more direct comparisons with our previous experiments the movement hand could vary between trials, while Baldauf et al. always had participants move their right hand. The task demand of having to select the moving hand may have made it more difficult to allocate attention to both movement targets. Another difference is that at the start of their experiments Baldauf et al. calibrated the task difficulty of the DT discrimination individually for each participant. Meanwhile, the perceptual task used in our sixth and seventh experiments were clearly too difficult for our participants, even though the latter had DT-presentation times as high as 300ms (five times that of Baldauf et al.'s fifth experiment). It may be that our perceptual tasks have just been too difficult and therefore insensitive for the size of the perceptual discrimination that we are attempting to detect.

In this final empirical chapter we aimed one more time to replicate the results of Baldauf et al. (2006), but this time we also carried out a pre-test session in order to calibrate the difficulty of the discrimination task for each participant. We focused on their pre-test session and attempting then to replicate Baldauf and colleagues' first experiment and pre-test session more closely. The differences between their work and ours are outlined at the end of each procedure.

We expected not only to succeed in replicating the so far elusive results of Baldauf and colleagues, but also that when the results of the last 4 blocks were compared to the first 3 (which in the original study were used as practice blocks), we would observe a gradual improvement of the DT discrimination, if not at the first movement target, then at the second one. However this expectation was not fulfilled. The issues began with the pre-test session being more challenging than expected, with only close to a third of participants managing to achieve the required discrimination performance (i.e. they were GPPs). When these GPPs had to perform the double-step pointing in the experimental sessions, they exhibited perceptual enhancement only at the first movement location. The reasons for this third failure to replicate will be elaborated on in the discussion section.

6.1.2 Pre-test Session: Method

6.1.2.1 Participants

Twenty-three participants (12 females, 11 males, mean age = 23.0 years, SD = 5.45) took part in the pre-test session. They had normal or corrected-to-normal vision (though no glasses as this interfered with the eye tracking) and were right-handed by self-report. All were reimbursed £5 for their time. This study was approved by the Psychology Research Ethics Committee, University of Edinburgh.

6.1.2.2 General Set-up

The general set-up and equipment were the same as those used since Experiment 5. The main differences lie in the stimuli used. The fixation cross had the same proportions as in our previous studies, but was surrounded by 12 figure 8's, which were the same size as in Baldauf et al.'s study (0.9° X 1.4°). The figure 8s were arranged in an imaginary circle around the fixation cross with a radius of 7.2°. The fixation target was 339mm up the working surface. These changes meant that the figure 8s not only were more numerous than in our previous studies, they were also slightly smaller and closer to fixation. As in Baldauf et al. (2006), participants used only their right hand, which had as the starting position the location on the working surface matching the fixation cross.

6.1.2.3 Procedure

The trials sequence can be seen in Figure 6.1 (p. 182). Following the drift correction, the initial screen was presented to the participant. The red LED was on, thus giving them the opportunity to place their right index finger at the appropriate starting position, if it was not there already. Once the hand was adequately placed, then the red LED switched off and the trial began. The initial screen was presented for 580-880ms, and this was then followed with the presentation of the cue screen (50ms). This consisted of a black arrow replacing the fixation cross and pointing at the first movement target. Subjects were to point at said target as quickly and

accurately as possible. If the locations of the figure 8s are compared to those of numbers on a clock, participants were only instructed to move to the targets at the “1”, “3”, “5”, “7”, “9” and “11” locations. The arrow remained on the screen until the end of the trial. The cue screen was followed by the probe screen (120-280ms), where the DT was presented at the location of the movement target. This was followed by a screen identical to the cue screen, and 3000ms after the red LED switched off, it switched back on again. This provided feedback to participants on their pointing accuracy and also indicated that they could blink and break fixation. The participant also used the presence of the LED to move their hand back to the starting position. This was followed by a black screen with white text saying “E or 3?”, which prompted subjects to provide a verbal response on the identity of the DT.

Although the DT always appeared at the movement target, its presentation time varied from trial to trial, in order to assess how long the DT needed to be presented for to elicit 80% accuracies. Participants carried out a practice block of 20 randomly selected trials, which was then followed by 3 blocks of 48 randomly shuffled trials. In our pre-test session, each participant was probed at four different presentation times, and each of the 6 movement targets was pointed at 8 times, resulting in pointing twice at each target per probe presentation time. The range of presentation times varied between the participants, as the initially selected range of times appeared too challenging for most of them. The first 6 participants had the DT presented for 120, 160, 200 and 240ms, and the subsequent ones were tested with times ranging between 160-280ms.

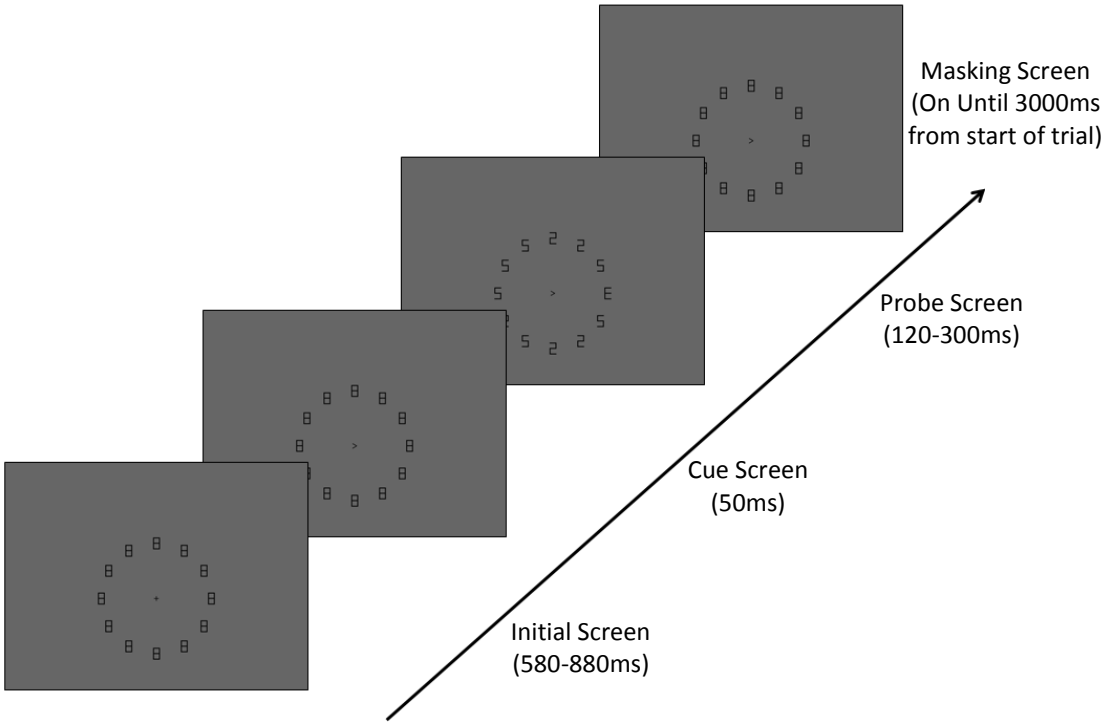

Figure 6.1. Trial sequence for both the pre-test and experimental sessions. Before the start of the trial the red LED was on in order to allow subjects to place their right index finger on the fixation cross (*not shown*). Once this was achieved, it was switched off until the end of the trial. The initial screen was on for 580-880ms, which was followed by the cue screen, in which the fixation cross was replaced by an arrow (50ms). In the pre-test session subjects performed a single pointing movement to the indicated target, and in the experimental session this was followed by a second movement to the figure 8 two positions along in a clockwise fashion. This was followed by the probe screen, which was on for differing amounts of time depending on the session and participant. In the pre-test session the cue screen was on for 120-280ms, while in the experimental sessions the DT was presented for between 240-300ms, depending on time necessary to achieve 80% accuracy in the pre-test session for that participant. This was followed again by the cue screen, which was on for 3000ms from the start of the trial. Following this the red LED switched back on signalling the end of the trial and that subjects could now break fixation, while also providing them feedback on their pointing accuracy. This was followed by a response screen in which participants reported which DT had been present.

6.1.2.4 Differences between the pre-test sessions

As stated at the end of the introduction, there were a few differences between our pre-test sessions and those conducted by Baldauf.

The first difference concerns the discrimination success rates we aimed to achieve. Whereas Baldauf et al. (2006) calibrated the task in the pre-test session to yield discrimination accuracies of 85% at the movement target, we opted for a slightly lower target of 80%. This was done as we once more had difficulties in finding participants who could carry out the perceptual task. However 80% accuracy is considerably above chance, and thus satisfying the requirements of the task being well calibrated in difficulty.

For this reason the range of our presentation times were higher than those used by Baldauf et al. (2006), although they did not report how the times used during the pre-test session were selected nor what they precisely were for each participant. They used a range between 150-230ms in their pre-test session, and following this the mean time they used in their experimental sessions was 190ms. For our first 6 participants the DT was presented for between 120-240ms, but as none of these participants managed to carry out the task at 200ms or below, the subsequent participants were tested with times ranging between 160-280ms, which still encompassed the mean presentation time used by Baldauf et al. (2006). Longer presentation times would have also increased the number of trials in which the DT was still present at movement onset, which we wanted to avoid. As none of our participants ended up performing at better than chance levels with presentation times of 200ms or less, this choice appears to have been justified.

We also slightly increased the number of trials in an attempt to achieve a reliable calibration of the perceptual task. Whereas the pre-test session carried out by Baldauf et al. consisted of a single block of 96 trials, we conducted a short practice block of 20 trials, followed by three blocks of 48 trials. We still kept the number of trials relatively low, so as to minimise any potential practice effects.

Another small difference was the medium through which participants reported the identity of the DT. As in our previous experiments, in our version participants reported the identity verbally, and it was then keyed in by the experimenter, while in Baldauf et al.'s study the response was keyed in by the participants themselves. We did not anticipate this to have an effect on participant responses, and this difference was present also in the experimental sessions.

The stimuli used by us were the same distance from the central cue and had the same size in terms of visual degrees as Baldauf et al. (2006), but as they did not report the size of the central cue, we used the same size as we had used since our fifth experiment. We also did not use the

same luminosity levels as Baldauf et al. (2006) due to the malfunctioning of our colorimeter, but like them we had black stimuli on a grey background.

6.1.2.5 Data Treatment

In order to minimise the time period between the pre-test session and the experimental session, the estimation of the DT presentation time necessary for 80% discrimination accuracies was obtained from data which had had only the practice blocks and trials in which a saccade had occurred removed. However this should not have been an issue due to the overall low number of trials removed in previous experiments. For example, in Experiment 5 which also consisted of a single pointing movement to one of 6 targets (albeit with either hand), only 7% of trials were removed. As we shall see this calibration was successful, as in the subsequent experimental sessions the discrimination performance at the first movement location did not significantly differ from 80% (p. 194).

The responses at the different target locations were collapsed together, and the mean discrimination accuracy was obtained for each DT-presentation time per participant. (It bears remembering that the DT always appeared at the movement target.) These mean accuracies were then plotted against the probe presentation times, and a line of best fit was produced. This line of best fit was used to estimate the presentation time required to produce accuracies of 80%, to the nearest 10ms. Subjects had to reach over 70% accuracy within the time range they were tested for them to be classified as being able to do the task, and for it to be deemed possible to estimate the probe time which would result in 80% performance.

Following the division of subjects between those who could do the task and those who could not, and estimating the DT-presentation times for the former group, a more rigorous filtering of the data was carried out. As per usual, trials in which the markers were occluded were removed from the sample (0.51%), as were trials in which subjects pointed to the incorrect target (6.69%) and in which the movement was initiated within more than two standard deviations from each participants' mean RT (5.08%). We were interested in assessing whether

there were any differences in kinematic performance between those who could and those who could not perform the discrimination task above chance levels. It might be that subjects with poorer performance in the discrimination task had poorer selection of the movement target, although we did not find this effect in Experiment 5.

6.1.3 Pre-test Session: Results

6.1.3.1 Perceptual Performance

The main purpose of the pre-test session was to estimate the length of the DT-presentation time required to achieve 80% discrimination accuracy. Table 6.1 (p. 186) shows the weighted means for the different presentation times. Only eight of the subjects managed to reach the required levels of performance (i.e. they could be grouped as GPPs), and the calibrated presentation times ranged between 240-300ms (M = 276ms, SD = 21). The mean performance at the different presentation times when divided between those who could do the perceptual task and those who could not, can be seen further illustrated in Figure 6.2 (p. 186).

We conducted a series of independent samples t-tests to investigate at what presentation times did the performance start to change between the two groups. Performance did not differ between GPPs and BPPs for the three shortest presentation times ($t(4) = 0.62$, $p = 0.57$, $d = 0.62$, $t(20) = 0.46$, $p = 0.65$, $d = 0.21$ and $t(20) = 1.32$, $p = 0.20$, $d = 0.59$ respectively). However it did for the two longer presentation times (240 and 280ms) ($t(20) = 4.73$, $p < 0.001$, $d = 2.12$ and $t(14) = 4.61$, $p < 0.001$, $d = 2.46$ respectively).

Table 6.1. Mean DT discrimination rates (%) for the different presentations times for each participant. For the participants who managed to progress to the Experimental Sessions, the calibrated presentation time can be seen in the 'Calibrated Time'-column. These participants have further been highlighted in bold.

Subject	120	160	200	240	280	Calibrated Time
1	42.88	34.64	47.95	45.20	-	-
2	**37.58**	**40.30**	**41.02**	**73.33**	**-**	**260**
3	**50.00**	**44.44**	**58.33**	**77.78**	**-**	**240**
4	35.59	33.13	45.91	52.08	-	-
5	32.46	20.59	26.67	25.98	-	-
6	45.92	41.67	49.23	32.46	-	-
7	-	59.50	43.42	55.21	66.67	-
8	-	45.61	46.05	46.24	45.59	-
9	**-**	**54.51**	**53.51**	**75.83**	**71.57**	**300**
10	-	35.45	38.89	42.81	38.012	-
11	-	48.83	47.21	31.54	38.89	-
12	**-**	**40.94**	**44.27**	**60.99**	**85.78**	**280**
13	**-**	**46.20**	**62.34**	**80.56**	**88.89**	**260**
14	**-**	**34.15**	**59.21**	**44.74**	**75.0**	**300**
15	-	41.18	48.82	25.82	49.86	-
16	-	19.44	30.56	33.75	55.11	-
17	**-**	**48.69**	**43.89**	**62.75**	**83.33**	**280**
18	-	46.35	51.40	65.52	62.43	-
19	-	44.27	25.65	44.44	59.50	-
20	-	44.12	54.44	52.78	44.44	-
21	-	57.03	66.67	52.78	45.32	-
22	**-**	**44.93**	**55.56**	**75.58**	**80.56**	**290**

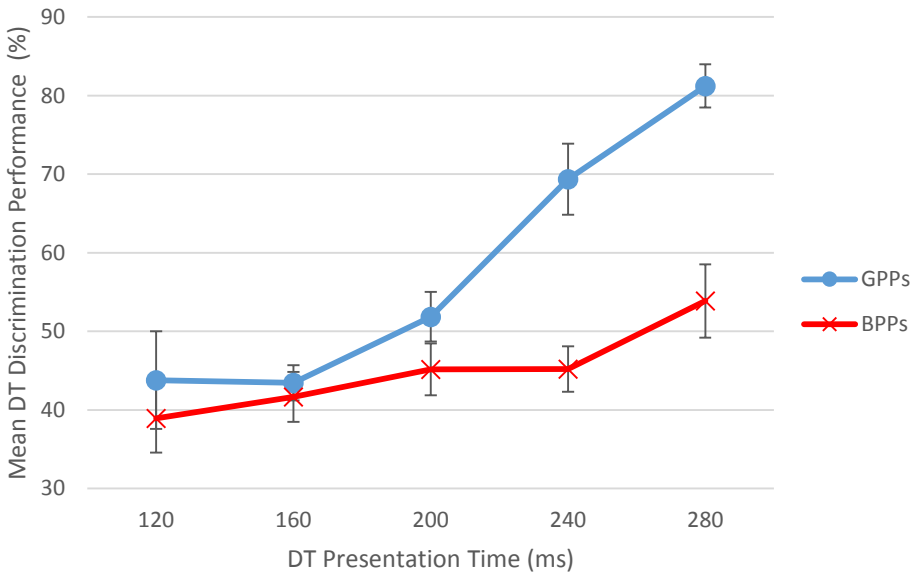

Figure 6.2. Average DT discrimination accuracies for the different presentation times divided by participants who reached the required levels of performance (GPPs) and those who did not (BPPs). The error bars represent standard errors.

What was the point in time at which perceptual performance increased above chance, if it ever did? The results of a set of one-sample t-tests conducted on the two types of performers can be seen in Table 6.2 below. If multiple comparisons are taken into account, then GPPs perform above chance levels only at times of 240ms or above. However what is more interesting is that BPPs never exceeded chance levels of performance, not even at the longer presentation times.

Table 6.2. DT discrimination means and SDs for the good perceptual performers (GPPs) and bad perceptual performers (BPPs) at the different presentation times. The perceptual performance of good performers was above chance at times above 200ms, whereas BPPs did not significantly differ from chance even at presentation times of 280ms.

Presentation	GPPs				BPPs			
Time (ms)	M (%)	SD	t	p	M (%)	SD	t	p
120	43.79	8.78	0.18	0.89	38.92	8.67	0.81	0.48
160	43.45	6.35	0.45	0.68	41.64	11.89	0.34	0.74
200	51.86	8.91	3.00	0.020	45.17	12.23	0.83	0.42
240	69.36	12.75	5.74	0.001	45.19	10.81	0.95	0.36
280	81.23	6.76	11.08	<0.001	53.86	14.8	2.01	0.076

6.1.3.2 Movement Performance

The pattern of movement end-points can be seen in Figure 6.3 (p. 188), and the movement parameters for both groups can be seen below in Table 6.3.

Table 6.3. Descriptive statistics on the different movement measures divided by good and poor perceptual performers. The two groups did not differ from one another.

	Good perceptual performers (GPPs)		Poor perceptual performers (BPPs)	
	M	SD	M	SD
RT (ms)	644	185	564	189
MT (ms)	419	74	397	88
M1 LA (mm)	19.65	7.07	18.49	4.77

In Experiment 5 we failed to find differences in movement performance between participants who could and could not detect the DT. The results of the pre-test session squarely replicate those findings. There was no significant difference in RTs ($t(20) = 0.59$, $p = 0.56$, $d = 0.26$), LAs ($t(20) = 0.46$, $p = 0.65$, $d = 0.21$) or MTs ($t(20) = 0.96$, $p = 0.35$, $d = 0.43$) between the two groups. It will be interesting to compare the movement performance for the good

performers when they are doing single movements with their performance in the experimental sessions.

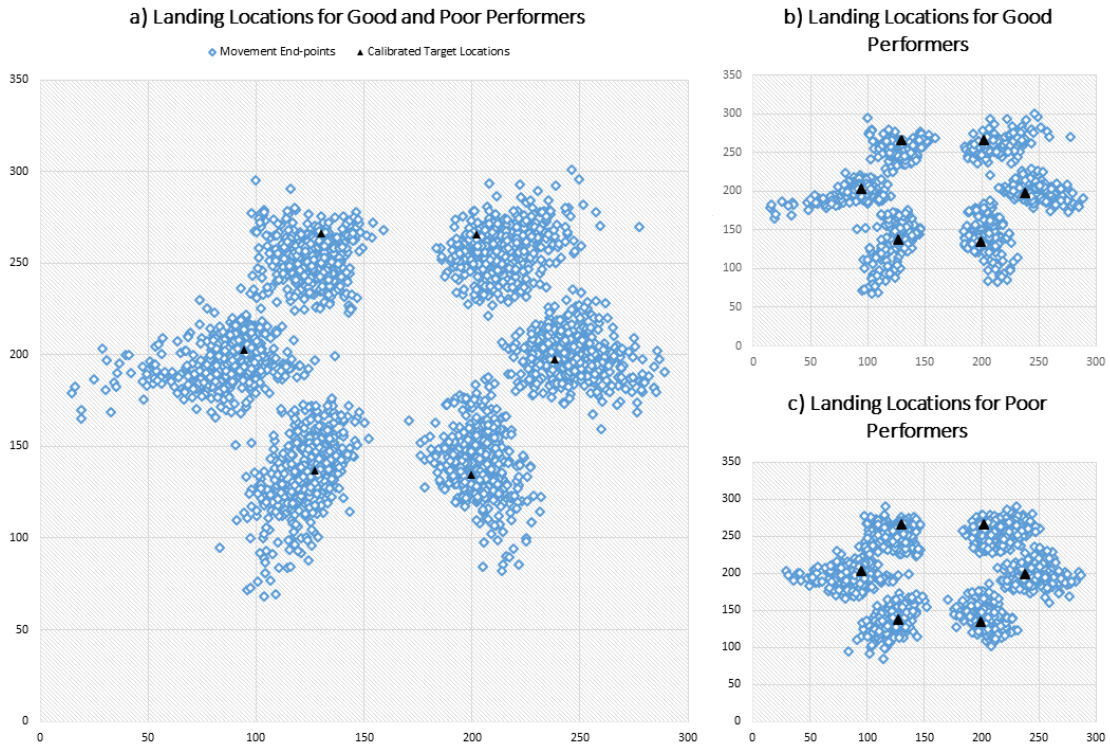

Figure 6.3. The pattern of movement end-points for both good and poor performers.

6.1.4 Pre-test Session: Interim Discussion

What is the most remarkable finding from the pretest sessions is how few participants managed to successfully discriminate the DT, even when it appeared at the movement location on every single trial. Out of 22 participants, we only found 8 (36.4%) who could perform at the required level, while the poor perceptual performers' results were at chance levels. Furthermore the DT presentation necessary to achieve good performance still averaged at 276ms, considerable higher than the presentation times used in much of the previous literature (e.g. Deubel et al., 1998; Jonikaitis & Deubel, 2011; Baldauf et al., 2006). That being said, these results bear comparing to some of the other work in the present thesis.

In terms of the presentation times required even for the good performers, the performance rates were considerably worse than we would have expected from our results from Experiment 5.

In Experiment 5, which used presentation times of only 150ms, good performers managed to achieve an accuracy rate of 75.5% at the relevant target location. There might be a few reasons for this. For instance, although the presentation times were shorter in Experiment 5, there were also fewer stimuli on the screen (8 vs 12), thus inducing lower levels of perceptual load. Furthermore, the sizes of the DT and the other stimuli in the circular array was decreased in the final experiment (down from 1.3° X 2.0° to 0.9° X 1.4°), which would have rendered the DT easier to discriminate. That being said, the eccentricity of the targets was lower for Experiment 8 (7.2°) than for our preceding experiments (8.1°), which would have compensated for the slightly smaller sizes of the stimuli. As a further point of comparison Jonikaitis and Deubel (2010) also used targets of the same size as Baldauf et al. (2006), albeit with slightly lower eccentricities (6.5°). However they presented their DT for only 80ms. Like in our last four of our experiments, their DT was also either an 'E' or a digital 3. It seems unlikely that bringing slightly smaller stimuli 1.4° closer to fixation can explain how Jonikaitis and Deubel (2010; 2011) managed to find better than chance performance at the different movement target locations at 80ms, whereas we had difficulty in finding participants who could discriminate the DT when presented for up to 200ms longer in Experiment 8, and having difficulties also from our Experiment 5 onwards.

Another interesting finding from the pre-test sessions which echoes the findings obtained in Experiment 5, is that worse perceptual performance did not translate to worse movement performance. This suggests that possibly, as far as manual movements are concerned, VSA and motor planning are not as tightly linked as the literature suggests. One could also argue that the perceptual task was too challenging for the majority of our participants, and therefore was not sensitive enough to detect any perceptual enhancement. Furthermore, as localisation requires fewer attentional resources, the attentional resources may still have sufficed for the purposes of action guidance (SfA) even when they were insufficient for discriminating the DT at levels above chance (SfP). This may be possible, but in that case the presentation times used

by the previous literature appear to be at the very least misleading about the perceptual ability of the general population.

What, though, are the consequences when an additional movement is introduced? Experiment 6, which was identical to Experiment 5 in terms of stimuli but introduced an additional pointing movement at the end of the first, found no evidence of perceptual enhancement at the movement relevant locations, which suggested that having to execute two movements rather that one may impair SfP. Doubling the DT-presentation time up to 300ms in Experiment 7 seemed to support this interpretation. However the difficulty of finding participants who could perform the perceptual task in the pre-test sessions suggests a more prosaic option: people who can perform well in a paradigm with multiple stimuli are relatively hard to come by. The fact that only 8 participants could successfully identify the DT in our pre-test session, and even then only when it was presented for 240ms or higher, makes the results of both Experiment 6 and 7 much less surprising. After all, even Experiment 5 found only 6 participants (out of 12) who could perform at above chance levels. Therefore perhaps the results obtained in the previous two experiments can be accounted for by the fact that their samples consisted of bad perceptual performers (BPPs). The performance of the 8 good perceptual performers (GPPs) in the upcoming experimental sessions will shed light on the matter.

6.1.5 Experimental Sessions: Method

6.1.5.1 Participants

Eight participants (4 females, 4 males, mean age = 25.0 years, SD = 6.23) took part in the test session. They had previously completed the pre-test session and succeeded in achieving over 70% performance for at least one of the probe presentation times. The testing was done across two sessions on consecutive days, and subjects were paid £24 for their time at the end of the second session. This study was approved by the Psychology Research Ethics Committee, University of Edinburgh.

6.1.5.2 General Set-up

The general set-up was identical to the pre-test session.

6.1.5.3 Procedure

The trial sequence was otherwise identical as to that of the pre-test session, with the exception that subjects now were required to point to a second target following the first target. Subjects were told to execute both movements as quickly and accurately as possible. As done by Baldauf and colleagues (2006), subjects were told that the discrimination task was going to be challenging, and that their key concern was to carry out the pointing as quickly and accurately as possible.

As stated in the pre-test section, the DT-presentation times were estimated so that it would result in 80% accuracy for each participant. The DT-presentation times ranged between 240-300ms (Mean = 276ms).

Once again, as in the pre-test session, the first and second movement targets corresponded to the locations on a clock face of the numbers "1", "3", "5", "7", "9" and "11". As in Experiments 6 and 7, subjects pointed first to the figure 8 indicated by the arrow, and then two locations along clockwise. Each block consisted of 96 trials, and each of the potential movement targets was equiprobable. On 25% of the trials the DT appeared at the 1st movement target and 25% of the times at the second movement target. In another quarter of the trials the DT appeared at the location between the two movement targets, so as to be able to control whether any benefit at both target locations was due to VSA having been split into two non-contiguous areas, or whether it was due to an enlarged spotlight of attention. Finally, in the last quarter of the trials the DT appeared equiprobably at one of the other 4 non-target locations. There were two testing sessions, the first one consisting of three blocks, which matched the three practice blocks carried out by participants of Baldauf et al. (2006). As in our experiment these blocks did not serve as practice blocks and were going to be analysed,

they were preceded by a short practice block of 10 randomly selected trials. The second testing session was conducted on the consecutive day, and consisted of 10 practice trials followed by four experimental blocks.

6.1.5.4 Differences between the experimental sessions

Once again, there were a few differences between our experimental sessions and those of Baldauf et al. (2006). As for the pre-test session, our participants reported their responses verbally. Also, the stimuli had the same set of stimuli as in the pre-test sessions, and as such we again did not match the luminosity used by Baldauf et al. (2006) and we used the same central cue as we used since our Experiment 5.

Baldauf et al. had three practice blocks followed by four experimental blocks, where each block consisted of 96 trials. They did not state whether participants conducted all of these trials in one session, but since this would result in multiple consecutive hours of testing per participant, we opted to the first three blocks on one day, and the last four blocks the following day. Due to this partitioning of the experiment sessions, each one was preceded by a short practice block of 10 trials in order to give the participants the opportunity to get to grips before the first three blocks, and get re-familiarised with the task on the second day. The length of the practice trial was kept low in order to still keep the number of trials close to that used by Baldauf et al. (2006). It bears noting that while Baldauf et al (2006) did not analyse the data from their first three blocks, we did, as we were interested in observing whether participants' perceptual performance may have improved during those three blocks.

Another difference between our work and that of Baldauf et al (2006) is that they had an additional component for prompting fast responses from participants. They used tones to give participant feedback on whether they had initiated their first movement quickly enough following the central cue, although they did not report what the criteria were. We did not incorporate this into our design as our kinematic analysis was conducted offline. However participants were prompted to respond as quickly and accurately as possible, and as before

trials with too long (or short) RTs were filtered out. The beep was also not seen as essential as Baldauf (2011) did not utilise it in a subsequent study which also found enhancement during multistep movements.

6.1.5.5 Data Treatment

The data treatment was in most respects the same as in the previous experiments, though there were some points worth mentioning. In this experiment the data from the different movement target conditions were collapsed together, and the perceptual performance was assessed by grouping the percent correct into four relative target locations: whether the DT had appeared at the first movement target, whether it had appeared at the second one, in between the two, or at another location. As in Experiments 6 and 7, the total movement time was deemed to be the time from the start of the first movement until the end of the second one.

In total, 3% of trials were removed because of incomplete kinematic data, 23% because of incorrect movements as deemed by having landed closer to another target than either of the intended target, and 1% due to the movement latencies occurring either 2SDs slower or faster than each participants' mean.

6.1.6 Results

6.1.6.1 Perceptual Performance

The perceptual performance of our participants can be seen in Figure 6.4 (p.194).

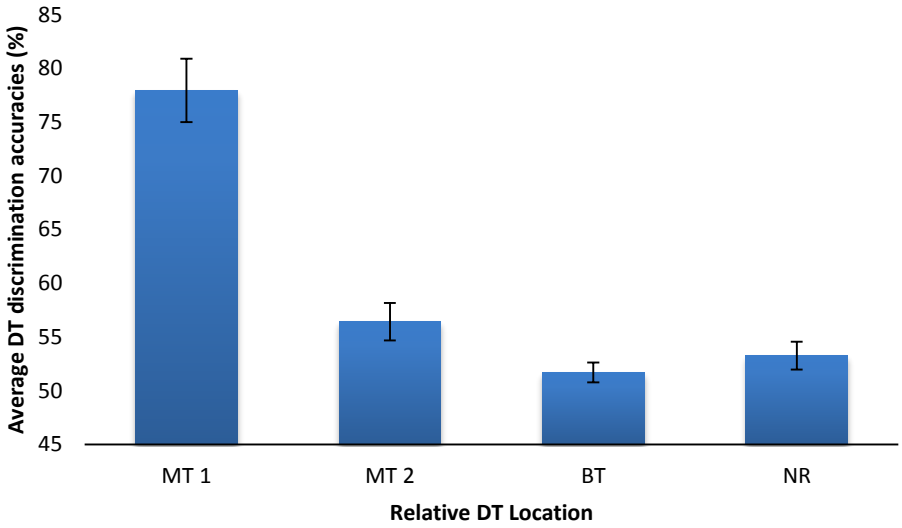

Figure 6.4. Mean DT discrimination accuracies at the different relevant locations. Error bars represent standard errors

The overall pattern of perceptual performance at the different relative locations can be seen in Figure 6.4. A repeated measures ANOVA on the discrimination accuracies found a significant effect of the relative location of the DT ($F(3,21) = 47.59$, $p < 0.001$, $\eta_p^2 = 0.87$), and post hoc t-tests found that performance at M1 was significantly better than at any of the other locations ($p < 0.001$). Furthermore, a one-sample t-test showed that performance at M1 did not significantly differ from our calibrated value of 80% ($t(7) = 0.32$, $p = 0.76$, $d = 0.11$), thus indicating that the calibration of the discrimination task was successful. In this respect our results did replicate the results of Baldauf and colleagues (2006): introducing an additional manual movement did not decrease perceptual performance at the first movement target.

We also found perceptual performance to be better than chance also at the M2 and NR locations ($t(7) = 3.73$, $p = 0.007$, $d = 1.32$ and $t(7) = 2.57$, $p = 0.037$, $d = 0.91$ respectively), but not at BT ($t(7) = 1.78$, $p = 0.12$, $d = 0.63$). Meanwhile, paired-samples t-tests found that performance at M2 did not differ significant from performance at BT ($t(7) = 2.21$, $p = 0.063$, $d = 0.78$) or at NR ($t(7) = 1.62$, $p = 0.15$, $d = 0.57$). Performance also did not differ between the BT and NR locations ($t(7) = 1.20$, $p = 0.27$, $d = 0.43$).

These results show that contrary to our first two attempts to replicate the results of Baldauf et al. (2006), Experiment 8 did find perceptual enhancement at locations beside the first movement target, perhaps most notably at M2. Baldauf et al. (2006) had also found that perceptual performance at M2 was better than at the non-target locations. In this respect we found that perceptual performance did not differ significantly between M2 and the other non-target locations, though the moderate effect sizes suggest that this may have been due to insufficient statistical power. Although we had two more participants taking part in our final Experiment than Baldauf et al. (2006), an even larger sample size could have helped differentiated between the performances at the different locations.

Although we were primarily interested in replicating the analyses conducted by Baldauf et al. (2006), due to the results pertaining to perceptual performance at M2, we conducted an additional generalised mixed effect model (GLMM) with a logistic link function in R's (version 3.2.4) *lme4* package. Our fixed effects were subject and movement sequence (i.e. which targets were involved in the movement). This found similar results to our t-tests, but for one difference. Performance at M2 was worse than at M1 ($\beta = 0.99$, SE = 0.095, $z = 10.37$, $p < 0.001$), and, as also shown by the t-tests, not significantly different from performance at NR locations ($\beta = -0.13$, SE = 0.086, $z = -1.53$, $p = 0.12$). However the performance at BT was revealed to be significantly worse than at M2 ($\beta = -0.23$, SE = 0.086, $z = -2.69$, $p = 0.007$). In contrast, there was no significant difference between perceptual performance at BT and NR ($\beta = 0.098$, SE = 0.085, $z = 1.15$, $p = 0.25$). This provides some further support for stating that attentional enhancement at M2 differed from that at non-target locations.

Our results therefore do offer some tentative support for additional enhancement at M2, though to a lesser extent than the work of Baldauf and colleagues (Baldauf, 2011; Baldauf et al., 2006). After all, in our experiment perceptual performance at M2 reached 56.4% compared to 75% in Experiment 1 of Baldauf et al.'s study (2006).

6.1.6.2 Did perceptual performance improve with practice?

One possibility as to why our results differ from that obtained by Baldauf et al. (2006) is that for their first experiment, the first 3 blocks were practice ones and were thus not included in the analysis, whereas we ran our analyses on all 7 blocks. The fact that so many practice trials were used suggest that it may take some time for some participants to perform at an adequate level when performing multi-step movements, even when the task has been calibrated based on their perceptual performance in one-step pointing movements. Performance in the first experimental session may have hidden the perceptual enhancements that take a while to emerge. We thus conducted another set of analyses only on the second experimental session.

There were no differences in the pattern of the results. Once again we found a main effect of location ($F(3,21) = 34.86$, $p < 0.001$, $\eta_p^2 = 0.83$), and performance at the M1-location was not significantly different from 80% ($M = 78.42\%$, $SD = 7.85$; $t(7) = 0.10$, $p = 0.92$, $d = 0.037$), suggesting no general improvement at that location. Meanwhile performance at the other locations did not differ from one another ($p > 0.30$), but performance at all of these locations were slightly above chance (Table 6.4). Conducting an additional 2 (Session 1 vs Session 2) X 4 (relative DT location) repeated measures ANOVA found that there was no main effect of session number on perceptual performance ($F(1,7) = 1.06$, $p = 0.34$, $\eta_p^2 = 0.13$). As before, the effect of the relative location was significant ($F(3, 21) = 41.79$, $p < 0.001$, $\eta_p^2 = 0.86$). These two factors did not significantly interact with one another ($F(3, 21) = 0.52$, $p = 0.68$, $\eta_p^2 = 0.069$).

Table 6.4. Mean perceptual performance at the different locations for trials in the second experimental sessions. Perceptual performance was significantly different from chance at all locations.

Location	Mean (%)	SD	t	p
M1	78.42	7.85	9.42	< 0.001
M2	56.63	6.82	2.76	0.028
BT	53.82	2.58	4.21	0.004
NR	54.65	5.32	2.51	0.040

The mean performance at each location type per block can be seen in Figure 6.5 (p. 197),

which shows little or no perceptual improvement at the different locations. However, may it be the case that the training effects are too subtle to be easily detectable, and such an effect may be masked by both analysing only at the session level and not taking into account variation between participants? An analysis at a trial level may therefore be more appropriate.

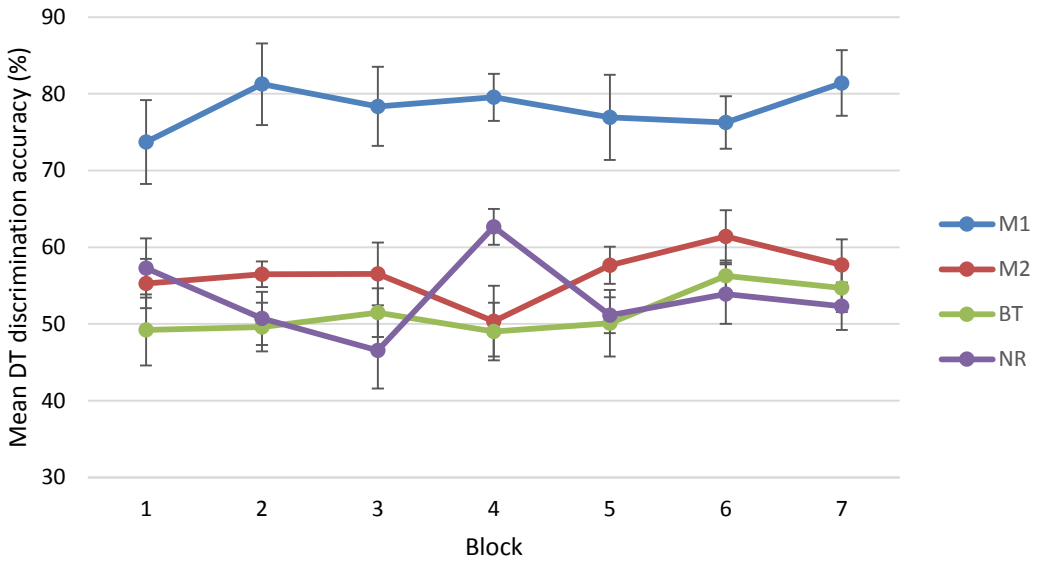

Figure 6.5. Mean DT Discrimination for the different DT locations per trial block. The first three blocks were part of the first experimental session and the last four blocks were conducted in the second. Error bars represent standard errors.

As our perceptual performance was measured as whether a participant correctly identified the DT or not, one has to remember that our data is binomial. For this reason the data per relative DT location across the 7 blocks were analysed with a mixed effect logistic regression (e.g. Jaeger, 2008). Our fixed effects were the trial and session numbers, and we included random effect for intercepts of participants. Our analysis did find some evidence for training effects, but subtle at best. Although we did not find a significant effect of trial number on accuracies (β = 0.00048, SE = 0.00037, z = -1.32, p = 0.19), we did find a slight but significant improvement between the first and second session (β = 0.15, SE = 0.066, z = 2.28, p = 0.023). This effect is slight which may be why it was not evident from our earlier analysis, but it highlights the importance of accounting for the level of experience of participants taking part in an experiment.

Although the primary purpose of running this analysis was to try and find practice effects, it may be worth mentioning that, unsurprisingly, this analysis supported our findings of better performance at the first movement target. The relative DT locations were dummy coded and compared with performance at the first movement target. As we already knew from our repeated measures ANOVA and can see in Figure 6.4, performance at M1 was significantly better than at M2 (β = -0.98, SE = 0.095, z = 10.37, $p < 0.001$), BT (β = -1.22, SE = 0.0094, z = - 12.89, $p < 0.001$) or NR (β = -1.12, SE = 0.0094, z = -11.79, p = 0.001).

Although we found some evidence suggesting that the second movement target receives a slight perceptual enhancement, this is at best much weaker than that reported by Baldauf et al., (2006) and may require a larger sample size to be convincingly demonstrated. However, we did replicate more convincingly another aspect of their findings, in that adding an additional movement did not decrease the amount of perceptual enhancement at M1. Analysing only trials from the second experimental session yielded the same pattern of results, and though we did find some evidence for practice effects across sessions, the improvements were minor.

6.1.6.3 Movement Performance

The overall movement landing patterns can be seen in Figure 6.6 (p. 198), while the means for the different movement parameters can be seen in Table 6.5 (p.198).

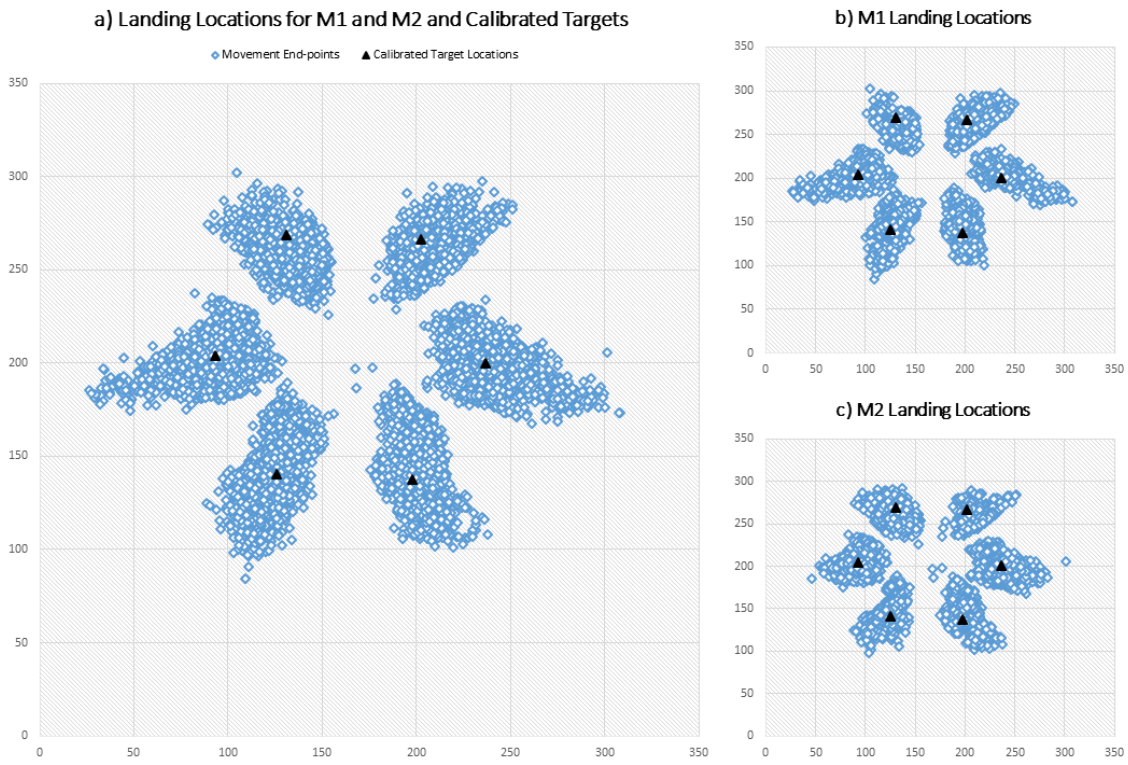

Figure 6.6. Overall pattern of the movement end-points for the different targets.

Table 6.5. Means and SDs for the different movement parameters for when the DT was presented at different locations.

	MT 1		MT 2		BT		NR	
	M	SD	M	SD	M	SD	M	SD
RT (ms)	533	55	533	55	534	55	535	62
TMT (ms)	960	171	955	180	959	180	960	182
BMT (ms)	204	138	198	144	202	145	203	148
M1 LA (mm)	17.4	7.14	17.4	7.39	16.8	6.55	17.1	6.99
M2 LA (mm)	15.1	4.88	15.0	4.28	14.6	4.11	15.1	4.26

As in the previous two experiments, we conducted a set of repeated measures ANOVAs with the DT's relevant location as a factor on the RTs, TMT, BMT, and LAs of the two movements. Baldauf et al. (2006) also carried out the same analysis, although only on the RTs, where they did not find a significant effect. We replicated such a finding on the RTs ($F(3,21) = 0.16$, $p = 0.93$, $\eta_p^2 = 0.022$). No significant effects were also again not found on TMTs ($F(3,21) = 0.29$, $p = 0.83$, $\eta_p^2 = 0.039$), BMTs ($F(3, 21) = 0.74$, $p = 0.54$, $\eta_p^2 = 0.095$), M1 LAs ($F(3, 21) =$

1.57, p = 0.23, η_p^2 = 0. 18) and M2 LAs (F(3,21) = 1.64, p = 0.21, η_p^2 = 0.19). This failure to find an effect of the DT's location replicates the effects found in our Experiments 6 and 7.

6.1.6.4 Additional movement analyses – Differences between movements and practice effects

As in the previous experiments, we conducted some additional analyses on the movement parameters. Experiment 8 allowed us to re-visit a question first explored in Experiment 5: are better movement accuracies and better perceptual performance linked? Contrary to Experiments 6 and 7, in the present experiment we did manage to find good levels of perceptual performance, although only at the first movement target. As perceptual performance is better at the first movement target, one could expect this to be reflected in better movement accuracies as well. Participants had better LAs when it came to their second movements rather than first (M = 15.0mm, SD = 4.28 and M = 17.3mm, SD = 6.80 respectively), though a paired-samples t-test found that this difference in accuracies between the two movements was not significant (t(7) = 2.22, p = 0.062, d = 0.79). This supports the conclusion that improved perceptual performance is not tightly linked to better movement performance, though once more the large effect size may indicate that the present result may be attributed to insufficient statistical power. It bears remembering that Experiment 6 also found that the second movement was more accurate than the first (although this was not the case in Experiment 7, possibly due to too small a sample size).

We managed to find evidence for subtle training effects when it came to perceptual performance, so a question which follows is whether movement performances may be more susceptible to practice effects. The mean RTs per block can be seen in Figure 6.7 (p. 201). As we can see, the RTs are decreasing with time which is consistent with practice effects. We ran a linear mixed effect model with trial number and session as fixed effects and random intercepts. This analysis found both significant effects of trial number (β = -0.043, SE = 0.012, t = - 3.67) and session number (β = -16.2, SE = 2.05, t = -7.91). Compared to the subtle practice

effects seen with perceptual performance, these effects are considerably stronger when it came to movement latencies. Using naïve participants may therefore be even more important when it comes to movement timescales. This may help us understand some of the differences between our work and that carried out by Baldauf and colleagues (Baldauf, 2011; Baldauf et al., 2006), and will be discussed further in the upcoming discussion section.

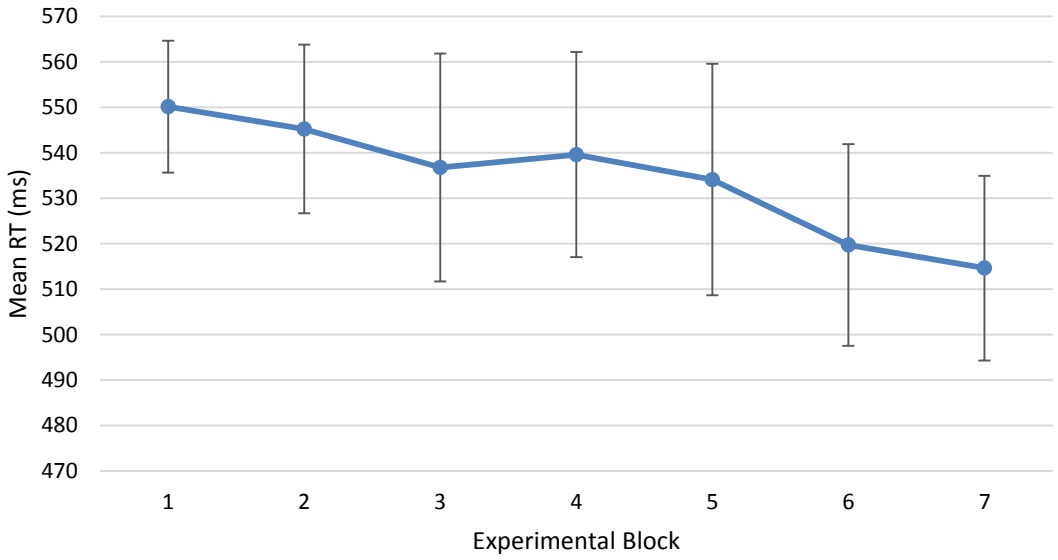

Figure 6.7. Mean RT per block. Error bars represent standard errors.

6.1.7 Discussion

Experiment 8 failed to replicate the robust findings obtained by Baldauf and colleagues (Baldauf et al., 2006; Baldauf, 2011), in that we found no clear evidence of perceptual enhancement at the second movement location beyond that allocated to other non-target locations. This may have been due to too small a sample size and insufficient statistical power, though our sample was larger than that used by Baldauf et al. (2006). We did find considerable enhancement at the first movement target, although this was following a pre-test session which proved to be too hard for about two thirds of our sample. This is not completely out of line with the work of Baldauf et al. (2006), as there too the first movement location received the most attentional enhancement. Also in line with their findings, we found that introducing a second movement target did not impair performance at the first movement target, so the more general finding that attention to the first movement target is not impaired by the introduction of other movement targets is supported. This tells us something important with regards to our two previous experiments: poor perceptual performance at all locations was not attributable to

participants having to execute a second movement, but due to the perceptual task having been too hard. Had it not been, we would have most likely observed enhancement at the first movement target. This interpretation is in line with the low rate of GPPs we had in the pre-test session of our final experiment, but is at odds with the probe times used in previous work (e.g. Deubel et al., 1998; Jonikaitis & Deubel, 2011). Regardless, the fact remains that we failed to find evidence for perceptual enhancement at the second movement target to the extent reported by Baldauf et al. (2006), and that participants who did exhibit perceptual enhancement at the first movement target were in surprisingly scarce supply.

6.1.7.1 No attention at the second movement target: Why?

Why did we find clear evidence of enhancement only at the first movement target? One of the main differences between the two movement targets is that the first one had an arrow pointed at it. Although Baldauf et al. (2006) found in a control experiment that an arrow unaccompanied by a movement to the indicated target did not orient attention, this control experiment was conducted with a separate set of participants. Our experiments suggest that participants who can perform the discrimination task in such paradigms are hard to come by, and as such it might have been that the 5 participants might have been what we have classified as BPPs. For this to have been a more valid control experiment, it would have required a second part where these participants would then perform the pointing movement and then exhibit enhancement at the movement targets.

One of the reasons why Baldauf et al. (2006) used separate participants for the above control experiment was that the participants they used in their main experiments "were all well trained to perform multiple motor sequences" (p. 4360), and they wanted to avoid them reactivating in motor imagery their pointing movements. This may go a long way as to explain our failures to replicate. The above statement could be taken to interpret that these participants were trained as a result of the experiments conducted in the above study, but it may also be the case that these participants had taken part in similar experiments before. Although when contacted Baldauf was kind enough to provide some information regarding the calibration session (i.e. mainly the ranges of times used) (D. Baldauf, personal communication, 13 December, 2013),

we received no reply regarding whether the participants were known to the experimenters in advance. However this appears likely, as the ranges of times used for the different participants varied. This would be consistent with having previous knowledge of each subject's ability, and thus being able to select time ranges in advance for appropriate calibration.

Our results found an effect of practice both on perceptual performance and movement execution. Although the effect on the former was slight and only seen at the session level, the cumulative effect that may arise from taking part in the different studies may be considerable in the long run. However we saw even stronger effects of practice when it came to RTs. Our participants had latencies on average 170ms higher than the participants in Baldauf et al.'s first experiment (523ms vs 349ms), and the gap between the initiation of the first and second movements in our experiment was 532ms compared to 284ms in their experiment. Baldauf et al. (2006) did not report their MTs, but it is likely that not only were the latencies of our participants slower, but they also took longer in executing their movements. When these considerations regarding their movement performance are coupled with the fact that our participants also required on average 85ms longer presentation times in order to achieve a slightly worse performance during the pre-test session (80% discrimination accuracies instead of 85%), even our 'best' participants were clearly 'slower' in both perception and action than those of Baldauf et al. (2006). Since our first experiments in the present thesis required presentation times of at least around 300ms for reliable discrimination performance, and the mean RTs in blocks in which the hand or target were known in advance (Experiments 1 and 4) were over 470ms, our results appear to be more representative of the general population. Although the effect of the arrow as a central cue is difficult to quantify, our results are consistent with attention being serially allocated in order to the first and second movement targets, and had we measured perceptual performance at a later point in the trial, we may have been able to measure perceptual enhancement at the second movement target.

Meanwhile, it is possible that the superior perceptual ability of the (potentially) more practiced participants in Baldauf et al.'s (2006) experiments allowed them to allocate attention to the multiple movement targets, in a serial fashion. As we discussed in the introduction to this chapter (p. 178), Baldauf et al.'s fifth experiment, which they argue supports parallel allocation of attention, is problematic both due to potential practice effects, but possibly more importantly due to the removal of several stimuli, which may have allowed a unitary focus of attention encompassing both movement targets (Awh & Pashler, 2000). It is also interesting to note that throughout the first four experiments in Baldauf et al.'s study, perceptual performance was always best at the first movement target, followed by performance at the second and third. The difference between perceptual performance at the first and second movement targets was significant in two of the experiments (1 and 4), and on the verge of significance in Experiment 2 ($p > 0.057$). Furthermore, the average difference in perceptual performance between the two first movement targets was always 10% or more. While performance between the second and third location never significantly differed, the performance was always worst at the third movement target (when there was one), at which perceptual performance was always significantly worse than performance at M1. In other words perceptual performance seemed to progressively decrease in the order in which the target was going to be acted upon (i.e. best at the first movement target and worse at the third), which would be consistent with serial shifts of attention, but the experiments may have not been sensitive enough to detect the differences, in particular as they had only 6 participants. This is important to point out because it indicates that perhaps their perceptual performance was underpinned by the same processes as our participants (i.e. sequential shifts of attention along the movement targets), but merely at a faster rate.

The speed of attention may not be the only potential factor. A latter study by Baldauf (2011) found that as the gap between the first and second movement increased beyond a certain point, the enhancement at the second movement target decreased. However this may have stemmed

from this stopping their participants from seeing the movements as part of a sequence during the longer intervals. Both our experiments and Baldauf et al. (2006) instructed our participants to execute the second movement as soon after the first movement as possible. In contrast, the participants in Baldauf's 2011 study were instructed to execute their second movements 100, 300, 500 or 700ms after the first one. They did not include an uninstructed condition as a baseline, but for the first two conditions the gap between the two movements was close to 300ms (even when it was instructed to be only 100ms). This suggests that in the two conditions with the lowest instructed gap between movements, participants were moving as fast as they could. It is only when the instructed timing increased to 500ms or above that the actual gap between movements started to increase, and the perceptual performance started to decrease. At the higher intervals the subjects were slowing down the execution of their movement sequences and therefore possibly seeing them as two separate movements, where the second target was attended at a later point in time. The importance of executing the movements as quickly as possible, rather than the actual gap between the onsets of the different movements, is consistent with Experiments 2-4 from Baldauf et al. (2006). In these experiments subjects performed a three-step pointing sequence, with a longer gap between the first and *third* movements, and yet found small amounts of decline. However when looked at closely, the mean gap in their third experiment between initiation of the first movement and second movement was 271ms, and the third movement was executed on average 240ms later. Therefore although the absolute interval between the different movements may not be critical (e.g. the gap between the first and third movement), both the continuity between the steps and the speed at which they are executed may be.

When told to keep the gap between movements down to 100ms or 300ms, the participants in Baldauf's 2011 study still had similar gaps between their first and second movements as the participants in Baldauf et al. (2006). They also were presented the DT a shorter time than for our participants (150ms; Baldauf, 2011) and had performance levels of 85% at the first

movement target and mean RTs of around 300ms, making them quite similar in ability to those participants employed in Baldauf et al.'s (2006) study, but not those in the present thesis. The gap between the first two movements in Baldauf (2006) being around 300ms or less suggests that their participants were performing as fast as they could, indeed as instructed. Although our participants received the same instructions (i.e. to perform the second movement as quickly after the second movement as possible), the mean gap between the initiation of the first movement and the second was 523ms, at which point Baldauf (2011) had found the performance at the second movement target was no different than at the non-relevant locations. Perhaps had our participants performed the movement even faster, we may have found attentional enhancement at the second movement location before initiation of the first. This difference in movement execution may therefore also account for our failure to replicate, but also suggests that providing the same instructions to untrained, unexperienced participants is not enough to replicate results. What may play a more critical role, is practice.

6.1.7.2 Practice makes perfect?

The role of practice in the work of Baldauf et al. (2006) may have been a significant factor in generating their results. After all, the participants were experienced in the task, if not all at the start of the experiment, then certainly by the end of it (mean accuracy rates at the first movement target in their fourth experiment was around 95%). Furthermore, their first experiment had three practice blocks of 96 trials each, and as we have said before this many practice trials being necessary for participants to understand the task seems unlikely. They do not look into practice effects, but what insights can we gain from other literature?

In Chapter 2 we covered the work of, Festman et al. (2013a, 2013b), who found that participants had enhanced perceptual performance along the trajectory of a manual movement being executed. In both studies they first trained their participants for 1-2 hours, until they could detect the DT at 75% accuracy when using presentation times lower than 200ms, by using a staircase procedure. Following the practice session, they maintained the staircase

procedure in place to account for any further improvement, and found that after between the subsequent 900-1200 and 1200-1500 experimental trials, the DT presentation time was decreased to on average 137ms and 85ms respectively (Festman et al., 2013a, 2013b). These are much stronger training effects than we ourselves found, but this discrepancy can be explained by the vast larger number of trials they conducted. Furthermore, their perceptual and motor tasks may have also been easier, as the former had only one stimulus on the screen beyond the fixation cross, and the latter involved moving the right hand from right to left and back again at a constant speed. Nevertheless this demonstrates the potential magnitude of practice effects on perceptual ability while executing a motor task.

Two experiments from Chapter 1 also highlight the role practice and perceptual performance. The first one is the work of Czerwinski et al. (1992), who found that following intensive practice, participants performing a search task could shift their attention at a rate of 30ms per item (p. 23). These very fast attentional shifts though are less surprising when considered they occurred after 50 days, and the sample size consisted of only two participants. Another example covered in Chapter 1 comes from the work of Ahissar and Hochstein (2000) who managed to train participants to detect a target in array, as the size of the SOA decreased three-fold during the course of training (p. 24). At the start, the SOA between stimulus presentation and the mask required to achieve 81.6% performance was on average around 170ms, but this decreased down to around 60ms. Such improvement took place over 1400 trials per session, and there were 8 sessions overall. They saw an average reduction in SOA of 70ms already between the first and second sessions. Our final experiment, in contrast consisted of only 672 trials which may go in part to explain why we only found minor training effects on perceptual performance.

All in all, this work demonstrates how one's participants can be trained to perform better in perceptual tasks, though it seems that for considerable improvement they may require more practice than our participants received. However, despite the differences in the tasks, the work

of Festman et al. (2013a, 2013b) shows that considerable improvement may be achieved already within a couple of hours. This strengthens the plausibility of the role of practice in explaining the better performance by the participants taking part in the studies of Baldauf and colleagues (Baldauf, 2011; Baldauf et al., 2006). As such their work may be more indicative of what the attentional system can be *trained* to do, rather than what it *does* in naïve participants.

6.1.7.3 The neglected role of individual differences

We will conclude this chapter by briefly mentioning an aspect that was not the main focus of our experiments but which emerges from the data as an important consideration in future work, and that is the role of individual differences, beyond the amount of experience a participant has with the task. After all, our participants in the pre-test session were all inexperienced, and yet could be divided into GPPs or BPPs, so practice is clearly not the only source of variation. Ahissar and Hochstein (2000) also found differences in the way in which attention was allocated before training, with participants who performed better at the start also having a larger spotlight of attention. Our research does not equip us with the ability to say much about the potential sources of variability, but some should be mentioned.

A tempting candidate for explaining individual differences in attention, is to attribute it to differences in the quality of cognitive faculties of the participants. After all, the mean RTs of the participants who took part in Baldauf et al.'s (2006) study had faster RTs than the ones who took part in our Experiment 8. This may have been due to training effects, but they may also have had faster RTs to begin with, which have been found in the past to correlate negatively with IQ (Deary, Der, & Ford, 2010; Jensen & Munro, 1979) and been taken to be indicative of faster processing speed. The study by Jensen and Munro (1979) even found a significant negative correlation between IQ and MT. Perhaps more crucially, IQ has also been linked with attention itself (Bates & Stough, 1997).

In the task by Bates and Stough (1997), participants had to respond to an illuminated light as fast as it appeared, and the number of potential locations at which the light could turn on (2 or 4) varied, as well as their spatial arrangement (either wide or narrow). Unsurprisingly, they found that participants with higher IQs had faster RTs, but they also found that the brighter subjects also performed relatively worse when the stimuli were more widely arranged. In contrast, some subjects in the lower IQ group performed better in the wide-arrangement condition. The benefits of IQ in relation to attention appear to be highlighted when the attentional spotlight is narrow, and to disappear in the wider arrangement-condition. This would pose problems for attributing higher IQs to Ahissar and Hochstein's better participants, as they also exhibited wider attentional windows, but perhaps this apparent discrepancy may be explained by the extensive training received by Ahissar and Hochstein's (2000) participants, and differences in the perceptual task.

Increased processing speed has been shown to be a factor in attention also through research onto the attentional blink (AB). Although the AB is a robust phenomenon, it is not universal, and an EEG study found that those who did not exhibit it had earlier P3 spike, thus suggesting that they were faster in processing the first stimulus (Martens, Munneke, Smid, & Johnson, 2006). This meant that they were then ready to process the second stimulus when it appeared. It is worth noting though that of the 207 participants who took part in that experiment, only 16 did not exhibit the AB, thus demonstrating how much more reliable the AB is compared to perceptual enhancement at the movement target location.

There are many other potential sources of variation in the perceptual performance of our participants beyond attention. For instance, recent work by Schwarzkopf and colleagues found that the size of V1 predicts the magnitude of certain visual illusions (Schwarzkopf & Rees, 2013; Schwarzkopf, Song, & Rees, 2011). Similarly merely eyesight itself may also play a role. These factors may be important to consider, as the better the visual representations are to begin with, the fewer attentional resources may be necessary to produce the same level of perceptual performance.

We have seen in the last section how many different factors may contribute in explaining differences in performance between participants. However there is one aspect which we have not yet discussed which relates to the earlier part of the present thesis i.e. the biases which drive attentional allocation. The strength of each bias does not have to be the same for each participant, be they due to differing internal goals or individual differences in the underlying neural architecture. This shall be discussed further in the final chapter.

Chapter 7: Discussion - Where does this leave us?

7.1 The Beginning of the End: A General Overview

7.1.1 The literature behind the research question

If one were to use the broadest of terms, the present thesis has been an investigation of the relationship between visuospatial attention and movement control. The answer to this initially innocuous-looking question is more complicated than initially may seem, with both sides of that relationship being challenging to understand on their own.

The first chapter focused on defining visuospatial attention, covering how it is allocated, its shape, and the role of attention in inhibiting distractors. Having covered these basics, the second chapter focused on arguably the central question of the thesis: the relationship between VSA and movement control. It also introduced different theoretical frameworks, mainly the influential premotor theory (Rizzolatti et al., 1987) and the too often overlooked VAM (Schneider, 1995), as well as the biased competition model (BC) of Desimone and Duncan (1995). Whereas the former two may have focused on how and why SfP and SfA are related to one another (i.e. why what we perceive may influence our actions, and vice versa), the BC account provides a framework to understand how different biases influence the allocation of attention. This helps explain the varying patterns of data seen across our experiments, and will be discussed further below. The second chapter also highlighted some differences between saccades and manual movements (e.g. Deubel & Schneider, 2003; McIntosh et al., 2010).

While the second chapter focused on the link between attention and movement, the third chapter looked at the link between attention and the body itself (e.g. Reed et al., 2006; Abrams et al., 2008). Attention is not only allocated to the target of upcoming movements, but also for monitoring one's peripersonal space. But if attention is allocated to the body when it is static, and also to both the target of a manual movement and along its trajectory (Festman et al.,

2013a, 2013b), is more attention allocated also to the starting point of the movement? This was the original question which seeded the subsequent experiments.

7.1.2 The Experiments

There were a total of eight experiments in the present thesis, the first four of which were covered in Chapter 4. These found that not only did our participants display enhanced perceptual performance at the movement target (Deubel et al., 1998) and at the hand locations (Reed et al., 2006) consistent with previous literature, but additional attentional resources were also allocated to the hand which was about to perform the manual movement. We dubbed this novel effect the relevant object bias, or ROB for short, and named the general bias at the hands hand bias (HB). However the different patterns of enhancement were only seen under the correct circumstances, such as when the task was of appropriate difficulty and the location of the DT unpredictable enough. This is in accordance with the BC account (Desimone & Duncan, 1995), where the pattern of attentional allocation is determined by the aggregate of several, sometimes competing, attentional orienting mechanisms. It is for this reason that they are merely biases. A similar view was also recently advocated by Baldauf and Deubel (2010).

In Chapter 5 we began by investigating the strength of the ROB further by making the perceptual task more difficult and increasing the number of potential targets. Here we found that perceptual performance was better than chance only at the movement target location, although only for half of our participants: the perceptual task was too challenging for the other participants. However, having made the perceptual task and target selection more difficult, it appeared that our participants allocated their limited attentional resources to the target selection. It appeared that the bias towards the movement target increased as selecting it became more challenging. Future work should investigate further how alternating the difficulties of different task components influence the pattern of attentional allocation, for instance, by systematically manipulating the potential number of movement targets. Interestingly, Experiment 5 also found no differences in movement performance between

those individuals who could perform the perceptual task and those who could not. It is possible that the attentional spotlight may have shrunk and focused to the highest priority location (Ahissar & Hochstein, 2000). Furthermore, the increased perceptual load may have led to the inhibition of the lower priority locations (Awh & Pashler, 2000; Lavie, 2005).

With these considerations in mind, that a more challenging task would lead to perceptual enhancement at only one location was not perhaps that surprising a finding. Nevertheless, Baldauf et al. (2006) had managed to find perceptual enhancement at up to three locations in parallel in a paradigm with more targets and an average DT-presentation time of about 190ms (range: 150-230ms). We theorised that perhaps movement targets might induce particularly resilient attentional biases for inducing multiple foci of attention compared to the HB and ROB. Three failed attempts to replicate the results obtained by Baldauf et al. (2006) makes this interpretation seem less tenable.

In the final empirical chapter (i.e. Chapter 6), we carried out our closest replication of Baldauf's work. Crucially, we attempted to calibrate the perceptual task's difficulty for each participant, who now only had to use their right hand throughout the experiment. Despite these changes, we struggled to find individuals who could discriminate the DT even in the calibration session, and those who did, failed to display evidence of perceptual enhancement beyond the first movement target. As in Experiment 5, there were also no differences in movement performance between those who could perform the perceptual task and those who could not. Interestingly, among those who could, the mean perceptual performance at the first movement target did not appear to decline with the introduction of a second manual movement, and at least in this respect our results do mirror the results of Baldauf et al. (2006). This also suggests that the poor perceptual performance rates observed in Experiments 6 and 7 were not a direct result of having introduced a second movement, but due to the perceptual task being too challenging for the participants in our samples. We also found subtle training effects on perceptual performance, and that combined with the movement data from the

participants who took part in the work of Baldauf and colleagues may be due to training effects, and not representative of the general population.

7.1.3 Recent evidence for the ROB: Mason et al. (in press)

At the time of writing of this final chapter, a paper was published online in NeuroImage which support the existence of the ROB. An ERP study found that the effector location (i.e. the starting point of a movement) received enhanced attentional processing simultaneously to the movement target (Mason, Linnell, Davis, & Van Velzen, in press). Subjects had to point with one of their hands to one of two targets, and 100ms, 200ms or 300ms after an auditory cue which signalled the instructed movement, a small white circle appeared for 100ms at either one of the potential target or hand locations. Subjects had to perform the movement as fast and accurately as possible. While the perceptual enhancement at the target locations was detectable at the different SOAs (as measured by the amplitude of the N1 ERP component), the effector-specific enhancement was found at the 200ms SOA. Nevertheless, this finding is in line with our finding of perceptual enhancement at all action-relevant locations.

The above study did not collect any behavioural measures of attention, and relied solely on ERP recordings. It is therefore possible that perceptual enhancements at the static hand at the early SOAs may have gone undetected, as at low SOAs both hands would have received similar levels of attention (as we found in Experiment 4), and only at later times would the ROB have enhanced the effector-hand more than the static hand (Experiment 3).

The above study itself did not provide their participants with a perceptual task. We therefore do not know what the detection rates of the small white circle were depending on where it appeared, and thus what the pattern of *perceptual performance* was. Although Mason et al.'s (in press) results are aligned with ours, our work also point to a more complicated relationship between attention and the effectors, whether static or not. These nuances may be undetectable in Mason et al.'s study due to the lack of a behavioural measure.

7.2 Main implications

The experiments summarised above have several implications. These are both theoretical and methodological in nature, and we will briefly review some of the key ones below.

7.2.1 On attention and action: The role of biases, and how target localisation does not warrant target identification

One of the key implications of the first four experiments in the present thesis is that participants have a bias to attend to locations relevant to the movement, including the movement effector. We dubbed this the relevant object bias (ROB). Both the premotor theory (Rizzolatti et al., 1987) and the VAM (Schneider, 1995) predict a tight link between perception and action, and our experiments in Chapter 4 do offer some support for this view, but also call for a more nuanced approach as the movement target is not the only source demanding attention. This can be understood via the BC-account by Desimone and Duncan (1995), which states that endogenous and exogenous sources of attentional orienting combine together to determine what is attended. Others since have proposed similar ideas, notably Awh and colleagues (Awh et al., 2012) who emphasised the role of previous experience (or *selection history*) in determining what is attended, in addition to endogenous and exogenous orienting. Within this framework, stimuli more likely to have become targets of attention in the past, are more likely to be attended, even when they are not relevant to the current task. In other words, while both the VAM and the premotor theory provide accounts linking perception and action, the BC-account highlights how that relationship is but one of many components which help determine the overall allocation of attention. An example from the present thesis of another factor which determines how attention is allocated is the hand bias (HB) found in Experiments 2 to 4 in Chapter 4. We will further discuss the implications these experiments have on both the premotor theory (Rizzolatti et al., 1987) and the VAM (Schneider, 1995) in section 7.2.2.

The latter half of our experiments further demonstrated that the relationship between action and perception is not as straightforward as some of the literature would lead us to believe (e.g. Deubel et al. 1998; Deubel & Jonikaitis, 2011). After having decreased the probe presentation times and increased the number of stimuli, we struggled to find participants who could successfully perform the discrimination task. That the perceptual task would become harder for our participants was not all that surprising considering that we had decreased the presentation times as well as increased the perceptual load, which may have rendered the discrimination task more challenging (MacDonald & Lavie, 2008). Yet we did not expect such poor perceptual performance.

Interestingly, Experiments 5 and 8 found no differences in the movement performance between participants who could and could not identify the discrimination target. Why was this the case? One key consideration is that localising a target requires fewer attentional resources than discrimination. Some evidence for this comes from the work by Posner et al. (1980) covered in the first chapter, who found smaller cueing effects in a discrimination task rather than in a localisation task (section 1.3., p. 14). Similarly, Wilder, Kowler, Schnitzer, Gersch, and Dosher (2009) found that while pointing at or counting dots impaired the discrimination of the orientation of a Gabor patch, its detection and localisation was unimpaired. A lower processing requirement for successful target localisation would explain why our participants performed the movement no differently whether they could discriminate the target or not. Their movement accuracies may have been as good as they were going to get considering they had no visual feedback to guide their movements following initiation. Furthermore, as far as the participants were concerned the movement execution, not the DT-identification, was the primary task. Considering then that attention is a limited resource, it may have been wasteful of them to allocate more attention than necessary for the motor task at the movement target if they had few if any attentional resources to spare.

However some participants *did* detect the discrimination target in Experiments 5 and 8, and this may have been due to differences in overall in perceptual or attentional faculties, as discussed in the previous chapter (p. 208-210). What is also possible is that there may be variation in the population in the strength of the different biases which determine the pattern of allocation of attention. The size of the bias pertaining to movement targets may have been stronger in these participants, thus resulting in sufficient levels of attention for perceptual enhancement to ensue. This is admittedly a speculative explanation, but one which is worth considering.

Our results also lend support to the work covered in section 2.4.1 in Chapter 2 which found attention beyond the movement target. For instance one of the studies conducted by Kowler et al. (1995) found that attention was allocated not only to the saccade target, but also to the locations adjacent to the saccadic end-points. Furthermore in their fourth experiment, they gave instructions to participants to either prioritise the perceptual or motor task, and when the two were given equal importance, this resulted in perceptual improvement at a separate perceptual target without a cost in saccadic execution. We also saw in Chapter 2 that Montagnini and Castet (2007) found that some attentional resources could be diverted from a saccade target, and that performance at the non-target location was influenced by the probability the DT would appear there (see also Born, Ansorge, & Kerzel, 2013). This contrasts somewhat with the results obtained by Deubel and Schneider (1996) who failed to find enhancement at a location beyond the movement target, even when the DT location was known in advance. We will discuss the issues of attempting to generalise from these studies in section 7.2.3. (p. 221), but first we will take a look at how the results from the experiments in the present thesis fit within the frameworks of the premotor theory (Rizzolatti et al., 1987) and the VAM (Schneider, 1995).

7.2.2 The present thesis, the premotor theory and the VAM

The main aim of the experiments in the present thesis was not to explicitly test between the premotor theory (Rizzolatti et al., 1987) and the VAM (Schneider, 1995). As such, they cannot be said to unambiguously support one framework over the other. However, of the two the VAM seems to fit our data more parsimoniously than the premotor theory, not in small part due to the more extreme claims and predictions of the latter, i.e. that planning a motor movement is equivalent to shifting attention and vice versa. Nevertheless, our work would suggest that both frameworks would have to be updated, although not to the same extent.

From Experiment 5 onwards we had difficulties in finding perceptual enhancement at the target location, possibly due to the perceptual task being too difficult for most of our participants. The times we did find perceptual enhancement, it occurred at the first movement target location (or at the target location if only one movement was performed). Failure to find attentional enhancement at the second movement target (when there was one) could be explained by there being sufficient time for the second movement to be planned after the first movement was initiated but before the second one was (Baldauf, 2011). In this respect, these latter experiments do not challenge either framework.

The biggest challenge to the premotor theory may come from the first set of experiments. These found perceptual enhancement beyond the movement target, at the locations of both movement's starting location and by the static hand. This further evidence for a hand bias (HB) (see also Abrams et al., 2008; Reed et al., 2006) suggests that motor preparation is not a prerequisite for the allocation of attention. It is possible that the enhancement found for the static hand may have been caused by the planning of an unexecuted movement. However this seems implausible, in particular when one considers the results from Experiment 4. The key factor is that as much attention was found to be allocated to the location of the static hand as to the starting point of the moving hand, even in blocks in which the same hand was moving on every trial. It seems unlikely that in these blocks the participants would have prepared a

manual movement with their static hands, at least consciously. Furthermore, if the perceptual enhancement seen at the static hand was due to movement preparation, following the work by Born et al. (2014) which found enhancement for executed saccades and not planned ones, then one would have expected the enhancement to have been higher still at the hand which executed the movement. Instead the performance was the same at both hand locations. Furthermore, the perceptual performance at the movement target was at chance levels, just as for the non-relevant, uncued target. Therefore, in Experiment 4 the planning or execution of a movement does not appear to play a role in allocating attention, and merely the positions of the hands does.

Although within a different paradigm, a similar argument against the premotor theory has also recently been made by Klapetek, Donikaitis and Deubel (2016), who found equal amounts of enhancement at the location an antisaccade was executed to as to the suppressed location (i.e. to the cued location the antisaccade was diametrically opposite to). The premotor theory, they argue, would predict more enhancement at the former location, as it was ultimately where the action was directed to. Our work would advocate towards relegating motor planning from being the same as attentional orienting, to merely being an important player in how attention is oriented, as already suggested by Klein in 1980.

The VAM on the other hand does not have the same problem. After all, according to it the way attention is allocated to a location is due to an aggregate of reasons, not just due to motor planning. Instead, the early processing of the attended 'object token' results in the additional processing of the spatial properties of the attended stimulus. Thus the fact that in Experiment 4 the static hand was attended as much as the movement relevant one is not a problem for the VAM, as the movement predictability may have prevented the effects that locations relevant to the movement would have otherwise contributed (Carlsen et al., 2009; Deubel & Schneider, 2003).

Where the original concept of the VAM stumbles is the allocation of attention to multiple locations. According to Schneider (1995, p. 357) the VAM primarily predicts that only one object token is attended at a time, thus proposing a unitary focus of attention, but does not address potential differences in the amount of attention within this focus. Our experiments which found enhanced perception at multiple locations (Experiments 2-4) did not probe the visual landscape in enough detail to determine whether this resulted from a unitary or non-contiguous distribution of attention. However Experiments 3 in particular found that the attentional distribution was not uniform among the attended locations, something which the VAM does not account for. Furthermore, although we could not find evidence for non-contiguous split of attention, the literature covered in section 1.6.3 on split attention suggests that splitting may be rare but not impossible (e.g. Awh & Pashler, 2000; Cave et al., 2010). It is possible that these results were due to quick serial shifts of attention, but this seems unlikely considering the poor perceptual performance observed in the present thesis with presentation times of 300ms or less. Furthermore, in Experiment 3 we found no effect of the point in time in which the DT was presented. As for the premotor theory, the findings for the latter experiments in the thesis (Experiments 5-8) can be explained by the perceptual task having simply been too hard for most participants, while failure to find enhancement at the second movement target may have been related to the time between movements, which allowed them to be planned sequentially.

The VAM thus needs to be updated to allow a more varied distribution of attention, where multiple sources compete for attentional resources and determine the overall distribution of attention. This is in line with the biased competition model (BC) of Desimone and Duncan (1995), and was also proposed recently by Baldauf and Deubel (2010). However, once the VAM is updated to allow a more nuanced and multi-peaked distribution of attention, then the mechanism it proposes for linking SfP and SfA is supported by our data i.e. attentional enhancement effects to early visual areas are propagated along the two different processing

streams. The results from Experiments 2 and 3 can be explained by either multiple object tokens of different strengths, or a single object token but represented at different intensities at different locations.

Overall, the work presented in the current thesis suggests that both theories need to be updated to fit the current data. However updating the premotor theory to state that motor preparation is only one of many factors determining how attention is allocated, would consist of a considerable downgrade for the claims of the theory and its explanatory power. As such, it would not be able to address our evidence for a hand bias. In contrast, once the VAM is updated to allow a more nuanced pattern of attentional distribution, it would be able to account for the separate contributions provided by both our HB and ROB. However the details of the interplay between these and other biases would require further investigation.

7.2.3 The generalisability of previous work and what it may actually tell us

Our last three experiments failed to replicate the findings obtained by Baldauf et al. (2006), which casts some doubts on the generalisability of their results. Using small sample sizes usually implies homogeneity of performance across the population. In other words, the effect is consistent enough for one to make conclusions about the larger population based on few participants. Yet, as we discussed in the previous chapter (see section 6.1.7.2), their findings may be a product of extensive practice. Their findings appear to be more indicative of what the attentional system *can* do rather than what it tends to do in everyday situations. This is an important distinction, and such work is informative in that it tells us about the limits of different cognitive mechanisms (in this case attention), and yet such experiments do not warrant extending conclusions on how the underlying cognitive systems operate in the general population. After all, one would want to be careful in making too many generalisations on how people tend to run and their abilities of the population based on the performance of Usain Bolt.

It is important to highlight that perceptual enhancement at multiple movement targets prior to movement onset (Baldauf et al., 2006; Baldauf, 2011) was not the only effect we had difficulty

replicating. After all, in our final experiment 14 participants (63.6%) could not reliably discriminate the DT when it appeared at the movement target, even with presentation times as long as 280ms. The seminal work by Deubel et al. (1998) used a presentation time as low as 150ms and used only 6 participants, while the work by Deubel and Jonikaitis (2010, 2011) used presentation times only 80ms long. These papers do not talk much about the level of experience of their participants in their discussions, yet at least in the work by Deubel et al. (1998) one of the participants was an author of the study and the others had previous experience of taking part in similar experiments. Furthermore, others have had difficulties in replicating similar perceptual enhancement at the saccade targets, although these efforts have not been published, exemplifying the file drawer problem (i.e. findings that fail to find significant results are less likely to get published). For instance, in an attempt by Wolfgang Einhäuser-Treyer, only 3 individuals out of 15 showed clear enhancement at the saccade target (W. Einhäuser-Treyer, personal communication, April 18, 2014). Meanwhile Sabine Born and her colleagues had also similar issues in replicating perceptual enhancement at the target of saccades, using the parameters using the parameters of Deubel and Schneider (1996). Some participants found the perceptual task too challenging while others managed to perceive the E and 3 at all locations (as one of our participants in Experiment 6) (S. Born, personal communication, April 18, 2014). At the very least these issues highlight how the parameters used in one experiment do not appear to reliably produce the same results, either because the effect is not present in the rest of the population, or it emerges only through practice, or because the effects are so subtle that they require more careful calibration than the literature suggests. Such lack of homogeneity in performance calls both for larger sample sizes being used in such experiments (certainly above 6 participants), as well as giving more prominence to the fact of whether naive participants were used or not, as well as more details about the calibration procedure. Finally, based on the potential role of practice and individual variability on the performance of such tasks, utilising a staircase procedure appears advisable, as this would maintain constant level of performance at a task throughout the experiment (albeit sacrificing

some ecological validity in the process, as the real world rarely counters any training that may be taking place). It is worth pointing out that the titration of the perceptual task simply by changing presentation times has its problems, as this could sometimes cause them to be too long before they would produce the required level of perceptual performance. Other ways of calibrating the perceptual task are available. For instance, Born and colleagues managed eventually to successfully calibrate their perceptual task and find enhancement at the saccade target by having their participants discriminate whether the vertical component of a cross ('+') bisected the horizontal line left or right of centre, and altering the eccentricity of the vertical line via a staircasing procedure (Born et al., 2013, 2014). Another potential alternative for calibrating a perceptual task is to ask participants to discriminate the orientation of Gabor patches, as the difficulty of the task can be easily manipulated by changing the contrast of the patch (e.g. Wilder et al., 2009). The work of Festman et al. (2013a, 2013b) is a step in the right direction as they used a staircasing procedure to calibrate their perceptual task, but also provided some indication of the amount of practice and improvement undergone by their participants. More work should strive to provide such information, which will surely assist in the replication of, and therefore also building on, the works of others.

7.3 Some unanswered questions and potential for future work

There are several avenues for future work on the basis of the current studies, including some questions which our experiments have not answered. For instance, across experiments, we saw a drop in mean perceptual performance following increasing the number of targets, and performance remained low even when we increased the presentation times to around 300ms, which implicates the increase in perceptual load as a cause. This may have caused the limited attentional resources to be focused to the location with the highest priority, which due to the increased number of potential movement targets were then allocated in selecting the intended one. Meanwhile the difficulty of selecting the movement effector remained unaltered, as did the total number of hands, so these biases remained equal in size and were thus overshadowed.

However our experiments never directly tested this, and it would have been interesting to conduct an experiment with varying number of potential movement targets. We might expect that the perceptual enhancement at locations beyond the movement target to gradually decrease as the number of potential movement targets increased. Furthermore, as the bias to attend near the hands and the bias towards the movement effector appear to be distinct, we might also find that the rate of decrease in the effect of either bias to differ from one another. One could also vary the number of potential effectors or hands present, but to a limited degree for understandable physiological limitations. A further control experiment could have also been conducted, where the perceptual load would have been varied (e.g. by increasing the number of distractors at locations that are never pointed to), while maintaining the number of potential movement targets constant. It is possible that such distractors would still be processed at some level as potential movement targets. Nevertheless these experiments could still reveal the extent to which the prioritisation of the movement target seen in Experiment 5 was driven by an increase in potential movement targets, or whether the movement target location tends to have a stronger attentional bias than the other locations, and thus be more resilient to increases in perceptual load.

Another question which could be explored further is the role of practice in the laboratory tasks that typify this literature. Although we saw some slight improvement in perceptual performance in the course of Experiment 8, the performance at the second movement target remained low throughout. Although we replicated the number of trials in the first experiment conducted by Baldauf et al. (2006), this would not have taken into account any previous participant experience on similar tasks, and other work suggest that training effects might require longer periods to have a large effect. For instance Festman et al. (2013a, 2013b) trained their participants for between one and two hours, while Ahissar and Hochstein (2000) trained their participants for 11,200 trials. Perhaps with further training our participants could have improved their perceptual performance and their movement latencies and reach the proficiency

displayed by Baldauf et al.'s (2006) participants. This could tell us whether their results are indeed due to practice effects, or whether there are other individual differences at play.

We have already mentioned that there is scope for more research to be done into individual differences in such paradigms. For instance, it may be that perceptual enhancement may be stronger in individuals with higher IQs due to better and faster processing (Bates & Stough, 1997; Martens et al., 2007). A related question is also how differences in behaviour in the laboratory translate to differences in behaviour outside of it. For instance Tipper and Baylis (1987) found that performance in an a questionnaire aimed to measure absentmindedness in everyday life predicted performance of how distractors were perceived in lab-settings. More absentminded individuals were more distracted by distractors, while in a second experiment negative priming effects (i.e. decrease in performance at a location which becomes relevant having been inhibited in the previous trial) were seen only in the less absentminded participants, supporting the view that more absentminded participants have less effective inhibition of distractors. Since we saw both good perceptual performers (GPPs) and bad perceptual performers (BPPs), it would be interesting to see what consequences this may have. Maybe BPPs may have poorer perceptual acuity in other tasks, or perhaps on the contrary they merely have better attentional control mechanisms, and as such are more sparing in allocating a scarce resource.

The present thesis focused on the relationship between manual movements and visuospatial attention (VSA), but it may be interesting to compare that relationship more directly with that between VSA and saccades. One could attempt to see whether the strength of perceptual enhancement in a saccadic task indicative of levels of perceptual enhancement seen in a manual task. Sandoval Similä, Buonocore and McIntosh (in preparation) have already found both similarities and differences between the relationship between VSA and saccades and the relationship between VSA and pointing movements. They found that although both manual movements and saccades to a target veered away from another covertly attended location, there

were differences between the two types of effectors. While vertical saccades exhibited larger trajectory deviations than horizontal ones, no such difference was observed between vertical and horizontal manual movements. Also, the magnitude of the deviations was much larger in the vertical saccades than for either type of manual movement, which were more akin in magnitude to horizontal saccades. Nevertheless, both effectors deviated away, possibly reflecting a common selection mechanism at least at the earlier stages, as predicted by the VAM (Schneider, 1995). In order to help unpick the extent to which the attentional processes overlap between the two types of movements, it would be interesting to conduct our Experiment 8 again but for both effector-types. Sandoval Similä et al. (in preparation) used different sets of participants in each version of the experiment, so this remains an open question. The degree to which there is an overlap in the target representation for both effectors could have interesting implications for the BC account (Desimone & Duncan, 1995).

There is a final idea for future work which we will cover, which is whether it is possible to combine the effects of attentional enhancement at multiple movement targets in an additive way. Baldauf and Deubel (2008) found that when participants had to execute a pointing movement with both hands simultaneously to separate locations, perceptual performance was enhanced in parallel at both movement targets. If both movement targets are independently allocated attentional resources, what happens when two movements are made, but to the same location? In other words, what if the participants were simultaneously pointing with both hands to the same target? Is attention then allocated independently by both hands, and then combined in an additive way, and thus potentially doubling the amount of attention at that location? If this was the case, perhaps a way to increase the number of participants who could discriminate the DT in our latter experiments would have been to have both hands executing the movements. At the other extreme, both effectors might combine to allocate sufficient attentional resources to execute the task at hand, i.e. target localisation, but no further, even though the location is the target of two actions. Perhaps if there is an advantage it may not be

displayed in the total amount of attention allocated to the target location, but in the speed in which the attention is allocated.

As we can see, there are multiple open questions and avenues for future research. As demonstrated in the present thesis the relationship between the allocation of VSA and movement control is a complicated one and can be hard to pin down, but it is for this reason that it is such a fertile ground for ideas.

7.4 Conclusions and Final Remarks

The seed from which the empirical work grew was a simple one: does planning an action allocate attentional resources not only to the movement target, but also to the effector's starting location? The answer to this question ended up being that it does, but only under appropriate conditions. One of the main theoretical implications which emerges from these experiments is that the way attention is allocated is dependent on the way different attentional biases interact with one another. Although the planning and execution of manual movements play a considerable role in the way attention is allocated, these are not the only factor and other locations may be prioritised over movement-relevant locations. Furthermore, the amount of perceptual enhancement, if present, may be more difficult to detect than some of the previous literature may suggest.

This should not be surprising when we consider that the attentional system has had to evolve to be both flexible and dynamic in order to adapt to an ever-changing environment and set of goals, all of which need to be dealt with limited resources. The focus of attention appears to be the product of multiple attentional orienting mechanisms, which may result in varying levels of perceptual enhancement. Much remains unknown about how these processes interact with one another, but it is to this discussion that the present thesis has aimed to contribute.

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Appendix – Published Paper:

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(Separate experiments designed and conducted as a research assistant prior to initiation of PhD).

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Look where you're going! Perceptual attention constrains the online guidance of action

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ABSTRACT

Action guidance, like perceptual discrimination, requires selective attention. Perception is enhanced at the target of a reaching movement, but it is not known whether selecting an object for perception reciprocally prioritises it for action. Two theoretical frameworks, the premotor theory and the Visual Attention Model, predict that this reciprocal relation should hold. We tested the influence of perceptual attention on the online control of reaching. In Experiment 1, participants attended covertly to a flanker on one or other side of a fixated target, prior to reaching for that target, which occasionally jumped, after reach onset, to the attended or non-attended side. Participants corrected their reaches for almost all target jumps. In Experiment 2, we required covert monitoring of the flanker *during* reaching. This *concurrent* perceptual task globally reduced correction behaviour, indicating that perception and action share a common attentional resource. Corrections were especially unlikely toward the attended side. This is explained by assuming that perceptual attention primed an action toward the attended location and that the participant inhibited this primed action. The data thus imply that perceptual selection constrains online action guidance, as predicted by the premotor theory and the VAM. We further argue that the fact that participants can inhibit a location within the action system but *simultaneously* maintain its prioritisation for perceptual monitoring, is easier to reconcile with the VAM than with the premotor theory.

1. Introduction

To support apt and skilful action, our visual systems must prioritise, specifying the spatial properties of goal objects and other relevant locations, and filtering out irrelevant information. Action guidance, like perceptual discrimination, requires selective visual attention (Allport, 1980). Because our visual experience feels unitary, we might naturally assume that we base our actions upon our explicit perceptions. But contemporary cognitive neuroscience suggests that this subjective unity is an illusion. There is extensive evidence for two broadly separate visual processing streams in the human brain: a ventral stream specialised for object recognition, and closely associated with perceptual awareness, and a dorsal stream optimised for the real-time guidance of action (Goodale & Milner, 1992; Milner & Goodale, 1995). A question that arises is whether vision-for-perception and vision-for-action depend upon shared or separable mechanisms of selective attention. That is, what is the relationship between *selection-for-perception* (SfP) and *selection-for action* (SfA)?

These functions cannot be entirely separate. Any object foveated for perceptual recognition, or as a target for action, will be processed within central vision, making higher acuity information about that object available for all behavioural purposes. But it is also possible to shift visual attention without movements of the eyes, providing possible scope for selection of different objects within different visual sub-systems. Milner and Goodale (1995) tentatively suggested an asymmetrical scheme, in which SfA determines the allocation of perceptual attention, but SfP does not reciprocally constrain action guidance (see also McIntosh et al., 2005; Milner, 1995). Other theories have proposed tighter relationships, the tightest being the unity implied by the premotor theory of attention (Rizzolatti et al., 1987). This influential theory proposes that spatial attention is instantiated within the pragmatic maps of the motor system, such that the planning of a goal-directed action (e.g. eye or hand movement) is both necessary and sufficient for a shift of visual attention to that location. That is, to attend visually to an object, we must plan a visually-guided action toward it, regardless of whether we subsequently execute that action, and the target of any such action will concurrently receive enhanced processing by the perceptual system. By the premotor theory, SfP and SfA should always co-occur, because they are one and the same.

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A further scheme has been advocated by Schneider, Deubel and colleagues across several empirical papers (e.g. Deubel & Schneider, 1996; Deubel, Schneider, & Paprotta, 1998; Schneider & Deubel, 2002), and forms one aspect of a broader neuro-cognitive Visual Attention Model (VAM, Schneider, 1995). The VAM proposes that vision-for-perception and vision-for-action share a selection mechanism, operating on early visual representations prior to the split between ventral and dorsal streams. Selection involves the chunking of these early representations to define an 'object token' corresponding to the target. The creation of this object token has the consequence that the object's perceptual features are prioritised for processing in the perceptual recognition pathway, whilst information about its location and spatial features is forwarded to the action pathway to generate a candidate motor response. In this scheme, the distinction between SfP and SfA relates merely to the behavioural motive for which an object is selected. The mechanism of selection is the same in either case, and the consequence is that the target is prioritised for perceptual processing, and simultaneously primes a motor response, which may or may not subsequently be executed.

As noted by Schneider and Deubel (2002), the VAM assumes that motor programming is a downstream consequence of visual attention, where the premotor theory implies that visual attention follows from motor programming.[1] This difference of detail will provide an important point of leverage to distinguish the theories with respect to our data in the Discussion. For present purposes, however, we emphasise the broader similarity between the two theories. Both predict that SfP should entail SfA and vice versa, and this prediction contrasts sharply with Milner and Goodale's idea that action guidance can be independent of perceptual attention (Milner, 1995; Milner & Goodale, 1995).

Many experiments have tested the impact of planning an action upon perceptual discriminations. In a now-classic experiment by Deubel and Schneider (1996), participants were centrally cued to perform a saccade to one of six lateralised locations, and were also required to report the identity of a probe, flashed at one of these locations during saccade preparation. Perceptual discrimination was enhanced selectively at the intended endpoint of the saccade, whilst remaining at chance levels even for immediately adjacent locations (1.5° distant). This yoking of SfP to SfA holds for manual actions such as reaching (Baldauf, Wolf, & Deubel, 2006; Deubel, Schneider, & Paprotta, 1998) and grasping (Castiello, 1996; Schiegg, Deubel, & Schneider, 2003). However, for delayed actions, in which the action target is known in advance, the mandatory yoking of SfP to SfA relaxes for manual actions, but remains strong for eye movements (Deubel & Schneider, 2003). It may be that predictable hand movements can be configured in advance and subsequently executed 'offline', without concurrent selection of the target, but that eye-movements, even delayed ones, always involve online SfA. This capacity for 'offline' manual responses may be one factor to explain some outlying null results. Bonfiglioli, Duncan, and Rorden (2002) found no perceptual enhancement at the target of a reaching movement when the hand and target were hidden, so that the reach was cued from memory rather than selected online.

So, the preparation of action influences the distribution of attention in perceptual tasks. Note that this has been established using tasks, like that of Deubel and Schneider (1996), in which the action target is selected endogenously, without any visual transient at that location. Under these conditions, any associated enhancement of perceptual discrimination can be interpreted as an effect of SfA upon SfP. This interpretation, however, would be less secure if the action were cued by a sudden-onset target; any enhanced SfP at the action target could then be explained by the exogenous effects of the target signal, rather than by the endogenous intention to act. This is vital to appreciate because, when we consider the converse question of the effect of SfP upon SfA, we find that almost no studies have framed the issue in a comparable manner. Instead, researchers have studied the effect of exogenous attention, such as sudden-onset visual distractors upon different aspects of action guidance. Such studies do not speak directly to the effect of SfP upon SfA, but they are nonetheless worth discussing, because they indicate the sorts of effects of attention on action that we might expect to see.

When a visual distractor competes (unsuccessfully) as a saccade target, this may be revealed as a bowing of the trajectory toward the distractor (e.g. McPeek & Keller, 2001; McPeek, Skavenski, & Nakayama, 2000), or away from it (Doyle & Walker, 2001; Godijn & Theeuwes, 2002, 2004; Ludwig & Gilchrist, 2003; McSorley, Haggard, & Walker, 2004). Similarly, manual reach trajectories can veer toward (e.g. Chang & Abrams, 2004; Chieffi, Ricci, & Carlomagno, 2001; Grierson & Elliott, 2008; Song & Nakayama, 2008; Tipper, Howard, & Jackson, 1997; Welsh & Elliott, 2004; Welsh, Elliott, & Weeks, 1999) or away from a salient cue or distractor (e.g. Gangitano, Daprati, & Gentilucci, 1998; Howard & Tipper, 1997; Tipper, Howard, & Jackson, 1997). These opposite patterns, of attraction and repulsion, can both be explained by proposing that the distractor initially primes an action response, producing attraction, but that top-down processes can inhibit that plan, producing repulsion (Tipper, Howard, & Houghton, 1998, 2000; Van der Stigchel & Theeuwes, 2006). Whether trajectories deviate toward or away from the distractor is thus determined by how much scope there is for top-down factors to inhibit primed responses toward it. Accordingly, veering is sensitive to task variables such as preparation time and prior knowledge (Laidlaw & Kingstone, 2010; McSorley, Haggard, & Walker, 2006; Tipper, Howard, & Houghton, 2000; Van der Stigchel & Theeuwes, 2005; Welsh & Elliott, 2004); participant capacity for top-down control may also be relevant, as pre-school children veer toward distractors from which adults veer away (Ambron, Della Sala, & McIntosh, 2012). However, for manual responses at least, attentional interference may be eliminated if the target location is known in advance, so that the reach can be pre-configured (McIntosh & Buonocore, 2012; Tipper, Howard, & Jackson, 1997).

As noted earlier, these effects of attention upon action, though interesting, do not show a specific effect of SfP on SfA. To test the specific effect of SfP requires attention to be allocated endogenously for perceptual discrimination, ideally when no visual change occurs that could bias SfA by an exogenous route. For instance, in Experiment 3 of Sheliga, Riggio, and Rizzolatti (1995), participants fixated a central symbolic cue that instructed them to attend covertly to one of four boxes, arranged in a square around fixation. The attended box contained a symbol that indicated whether a saccade should be made to an upper or lower target, vertically above or below fixation. All stimuli were on-screen from the beginning of the trial, so the shift of attention to the attended box was endogenous, and made solely to discriminate the symbol therein. Nonetheless, the attention shift induced a contralateral deviation in the trajectory of the ensuing saccade to the target. If we accept this deviation as evidence that a saccade to the attended box was primed and subsequently inhibited, then Sheliga's result indicates that SfP does indeed recruit SfA within the saccadic system.

[1] In a recent review article, Smith and Schenk (2012) represented the VAM as a model specifically of SfA, which "*proposes that covert attention is a necessary precondition for goal-directed movement preparation, but makes no assumptions about the involvement of the motor system in covert attention when goal-directed actions are not required*" (p. 1108). This may be a mis-reading of the original VAM, which in fact suggests that covert visual attention to an object will automatically prime actions toward it, whether or not the task requires goal-directed action (Schneider, 1995). The reading of the VAM that we adopt here has been confirmed as valid by the model's originator, Werner Schneider (personal communication, 4 March 2014).

The present study aims to test whether SfP similarly influences SfA during the online control of reaching. Online control is an important test case because it is probably the least disputed instance of a 'pure' dorsal stream function that might operate independently of the perceptual pathway (Glover, 2004; Rossetti, Pisella, & Vighetto, 2003; Schenk & McIntosh, 2010). For instance, Milner and Goodale (2008) have suggested that target selection for action may involve perceptual selection, but that online control is an autonomous function of the visuomotor system. Online control is typically studied using double-step tasks in which the target is jumped to a new location during a reach. Compensatory corrections are sufficiently rapid to be pre-conscious (Castiello, Paulignan, & Jeannerod, 1991), and occur even when participants are asked to react to target jumps in some other way, for instance by stopping the movement (Pisella et al., 2000) or diverting it in the opposite direction (Day & Lyon, 2000; Johnson, Van Beers, & Haggard, 2002). Corrections are unimpaired by concurrent performance of a cognitively demanding auditory n-back task, further underlining their automatic nature (McIntosh, Mulroue, & Brockmole, 2010). Automatic correction has even been observed in the context of visual extinction, a pathological attentional imbalance, causing perceptual unawareness of the visual feedback on which the corrections are based, which suggests that online control is independent of perceptual attention (Schenk et al., 2005).

Liu, Chua, and Enns (2008) have claimed to show that online control is similarly independent of SfP in the normal brain. These authors presented participants with a dual task, requiring them to monitor a rapidly changing stream of digits at fixation in order to identify a single target letter, and simultaneously to point to a peripheral visual target, which could either remain still or jump by 10 mm after movement onset. In their single task condition, the same stimuli were presented, but letter identification was not required. The perceptual dual task retarded movement initiation, suggesting an effect of perceptual attention on initial target selection, but the authors found no effect of the dual task upon pointing accuracy in either jump or no-jump trials. However, this is rather weak evidence for independence between SfP and SfA during online control. First, Liu et al.'s perceptual task did not just involve endogenous attention, but used a rapidly changing stream of digits, which would attract attention exogenously, regardless of whether the participant was instructed to monitor it. The freedom for SfA to be allocated differently between single and dual task conditions may thus have been limited. Moreover, the perceptual task, performed in central vision, seems to have been very easy, with letter identifications above 95% correct, so may have left sufficient spare attentional capacity to support adequate online control in the periphery, even in the dual task condition. Contrary to Liu et al., a study of reach-to-grasp behaviour, using a similar rapid serial visual identification task, but with prior adjustment of stimulus size and durations to ensure below-ceiling performance, did show dual-task interference with movement initiation, and with grip formation as the hand approached the target (Hesse & Deubel, 2011). Hesse and Deubel interpreted this as demonstrating co-dependence of SfP and SfA during both movement planning and online control. However, since they did not perturb the action target in any way after reach initiation, there was no direct demonstration of perceptual interference with online control (see also Hesse, Schenk, & Deubel, 2012).

In the present study, we aim to test specifically whether SfP constrains SfA during the online control of reaching. In two experiments, we manipulate the location to which perceptual resources are endogenously allocated, and study movement corrections when the reach target jumps to the same or opposite side of space. Thus, we use an exogenous visual probe (the target jump) to measure visuomotor responsiveness (SfA) to each side, as a function of endogenous perceptual attention (SfP). In Experiment 1, we vary the location of SfP immediately prior to reaching; in Experiment 2, we constrain SfP *during* the reach. If online guidance of action is independent of perceptual processing (Liu, Chua, & Enns, 2008; Milner, 1995; Milner & Goodale, 1995), then corrections should be unaffected. By contrast, both the VAM (Schneider, 1995) and the premotor theory of attention (Rizzolatti et al., 1987) predict that SfP will affect the likelihood and/or the extent of online correction. The *direction* of effect is less easy to predict, given that facilitatory and inhibitory influences of attention on action have been reported in previous work. However, the facilitatory or inhibitory nature of the effect may, as we shall argue, further discriminate between the VAM and the premotor theory.

2. Methods

2.1. Participants

Twelve participants (8 women, mean age = 22 years, SD = 2.73) took part in Experiment 1, and twelve different participants took part in Experiment 2 (8 women, mean age = 21.7 years, SD = 2.57 years) for £6 payment. All were right-handed by self-report and had normal or corrected to normal vision. This study was approved by the Psychology Research Ethics Committee, University of Edinburgh.

2.2. General set-up (Fig. 1)

Participants were seated in a darkened room with their head stabilised by the chin rest of an Eyelink 1000 (SR Research, Osgoode, Canada) video-based eye tracker. Stimuli were presented on a 21″ screen (400 × 300 mm active display, 1024 × 768 resolution, 100 Hz refresh) suspended face-down above a front-surface mirror via which the participants viewed them. The stimuli appeared optically to be on a slightly inclined working surface at the level of the participant's hand. The mirror was midway between the monitor and this working surface, preserving the optical sizes of the stimuli. The central target was 12 mm in diameter, and appeared to the participant to be 400 mm in front of the start button that their right index finger depressed at the start of each trial. Flanker stimulus locations were 75 mm to left and right of the central target. The display background was black, and all stimuli were white except where stated. Trials were always shuffled randomly. The mirror arrangement meant the hand was not visible to the participant. This aspect of the design was to ensure that there were no visual transients from the hand that could exogenously disrupt attentional allocation.

The Eyelink was used to monitor fixation, and trials were interrupted if the eye moved more than 30 pixels (~1.13°) from the central target prior to button release. A 5-point horizontal-vertical calibration was carried out at the start of the experiment and repeated as necessary, and drift correction was performed at the start of each trial. The Eyelink sampling rate was 1000 Hz. Pointing movements were monitored by attaching to the participant's right index fingernail an infrared emitting diode (IRED), which had its 3D location sampled by the Optotrak Certus system (Northern Digital Inc., Waterloo, Canada) at a rate of 100 Hz. The Optotrak was registered to the workspace, such that the start button was at the origin of a Cartesian coordinate system, and lay in the same *XY* plane as the targets so that the targets were at 400 mm on the *Y*-axis, with the central target at zero on the *X*-axis, and the two flanker locations at −75 and 75 mm (see aerial view of workspace in Fig. 4a).

2.3. Experiment 1 – SfP prior to reaching (Fig. 2a)

In Experiment 1, we required participants to attend covertly to one or other side of the central target dot, immediately prior to initiating a fast reaching movement. The initial display contained a flanking asterisk (12 mm diameter) on either side; the participant was required to fixate the central target but to monitor one or other asterisk for a change to a plus or a cross (by offset of the diagonal or the horizontal/vertical arms respectively). A cross signalled a NOGO-trial, in which the participant had to refrain from responding until the end of the trial 1000 ms later; NOGO trials were included to ensure that participants were accurately performing the required perceptual discrimination. A plus signalled a GO-trial, in which the participant had to make a rapid reach to the central target. On a subset of GO-trials, the target dot jumped either to the left or the right flanker position, thus either to the attended or non-attended side. The side to which participants were instructed to attend was manipulated on a block-by-block basis.

The participant was familiarised with the basic reaching task via a practice block of 45 trials. Practice trials were similar to subsequent experimental GO-trials, except that they did not require specific monitoring of one or other flanker location, allowing the participant to concentrate instead on the reaching demand. Each practice trial began with the participant fixating the central target and depressing the start button. After a delay that varied randomly between 750 and 1500 ms, both asterisks turned to plus signs, and the participant had to make a fast reach to the central target. On 15 trials, the target remained at the centre, on 15 trials it jumped to the left flanker position, and on 15 trials it jumped to the right flanker position immediately after button release. Any trial in which the participant released the start button before the flanker change, or moved the eyes from the centre before button release, was reshuffled. If participants did not initiate their reach within 750 ms of the flanker change on GO-trials, the words "Too Slow" appeared, accompanied by an error tone, and the trial was reshuffled. To encourage rapid reaches, a high pacing beep sounded 350 ms after button release, and participants were asked to try to complete their movements by the time of the beep. Participants were instructed to the leave the hand in its landing position until the target disappeared, 650 ms after button-release. The display was then replaced by the message "Press for next trial", and the participant returned the hand to the start button.

Following practice, each participant completed four blocks of experimental trials. These were similar to practice trials, except that in each block the participant was required to respond as instructed by the symbol that replaced the asterisk on one or other side, thus to reach if this was a plus (GO-trial), but not if it was a cross (NOGO-trial); the unattended asterisk simultaneously turned to a cross or a plus, but the symbol was perfectly uncorrelated with the symbol on the attended side. Each experimental block consisted of 50 experimental trials preceded by 15 practice trials drawn randomly from the trial sequence. The 50 experimental trials comprised 32 GO trials (20 no-jump, six jump-left and six jump-right) and 18 NOGO-trials. If participants released the start button on a NOGO-trial, they received an error tone and the on-screen message, "NO-GO Trial: Keep finger on button", but the trial was not reshuffled. The attended side was blocked according to an ABAB schedule, beginning with the left side for half the participants. Across the four blocks, participants thus completed 40 no-jump, 12 jump-left, 12 jump-right, and 36 NOGO trials per attended side.

Experiment 1 manipulated which side of space was endogenously attended, for the purposes of perceptual discrimination, immediately prior to reach initiation. This was not a 'pure' manipulation of SfP, since there were exogenous transients associated with the changing of the asterisks. However, these changes were visual offsets, which are of relatively low salience to visual attention (Cole et al., 2003) and, crucially, the asterisks on both sides of space always changed simultaneously, so that this exogenous component was spatially balanced. Any lateralised effects on correction behaviour should therefore be interpretable as due to the instructed allocation of SfP.

2.4. Experiment 2 – SfP during reaching (Fig. 2b)

In Experiment 2, we tied the SfP demand more closely in time to the reaching task, so that participants had to monitor the flanker continuously on one or other side for a subtle flicker during the reach. The side to which participants were instructed to attend was manipulated on a block-by-block basis, and participants were informed that the flicker would only ever occur on the attended side, though they were not told how often to expect it. Our main kinematic analyses were restricted to trials in which the flicker did not occur, so that we were able to study the consequences of attending endogenously to a location for perceptual discrimination, independently of that perceptual change occurring.

The basic trial sequence was similar to that of Experiment 1, except where indicated. At the start of each trial, the participant was required to fixate the central target and to depress the start button. The initial display contained a small (0.14°) mid-level grey square on either side. As soon as the participant felt ready, they were to reach rapidly for the central target and to monitor the grey square on one or other side for a flicker. On no-jump trials, the central target did not move; on half of these trials, the grey square on the attended side would flicker (i.e. disappear for 20 ms at button release); the square on the non-attended side never flickered. As in Experiment 1, rapid reaching movements were encouraged by a high pacing beep 350 ms after button release, and in Experiment 2 this was reinforced by the disappearance of the display after 350 ms. On no-jump trials, after a further 650 ms, the word "Flicker?" appeared in the centre of the screen, and the participant had to answer verbally "yes" or "no", their response being keyed in by the experimenter. On jump trials, the grey squares never flickered, but the target jumped to the location of the grey square on one or other side immediately after button release. On jump trials, the end of trial screen simply presented the word "Ready?", to which participants could respond verbally before initiating the next trial.

The participant was familiarised with the basic reaching task via a practice reaching block of 45 trials (15 no-jump, 15 jump-left, 15 jump-right), in which they were not instructed to monitor the grey dots. Next, they were familiarised with the basic perceptual task by performing two blocks of 20 no-jump trials, in which they monitored for a flicker on the left side in the first block, and on the right in the second, with the flicker occurring on half of the trials in each practice perceptual block.

Following practice blocks, each participant performed four experimental blocks. Each experimental block consisted of 60 trials preceded by 10 practice trials drawn randomly from the trial sequence. The 60 experimental trials comprised 40 no-jump trials, half of which contained a flicker on the attended side, and ten jump trials to either side. The attended side was blocked according to an ABAB schedule, beginning with the left side for half the participants, and the right for the other half. Across the four blocks, participants thus completed 60 no-jump trials with flicker, 60 no-jump trials with no flicker, 40 jump-left, and 40 jump-right trials per attended side.

2.5. Data processing and preliminary analyses

For Experiment 1, NOGO trials with saccades (11.1% of trials) or where participants released the starting button (4.2% of trials)

were considered failed. For both experiments, trials with incomplete kinematic information due to marker occlusion were discarded (1.1% of trials in Experiment 1, and 0.3% of trials in Experiment 2). For the remaining trials, raw kinematic data were filtered by a dual pass through a Butterworth filter with a cut-off of 20 Hz. Movement onset was defined by button release, and movement offset was defined as the final frame before which the speed of movement fell below 50 mm/s.

For Experiment 1, the following movement variables were extracted: reaction time (RT) from cue onset to button release; movement time (MT) from movement onset to offset; peak speed (PS) of movement; time to peak speed (TPS) from movement onset; amplitude of movement (AMP) from the IRED's start position to its final position in the *XY* plane of the workspace; terminal angle (ANG) of the IRED's final position with respect to its start position in the *XY* plane of the workspace. We also calculated reach curvature (CURV), using a computation adapted from Appendix A of Van der Stigchel, Meeter, and Theeuwes (2006). First, we transformed each reaching movement so that the straight line path from the start to the end point was aligned with the *Y*-axis. We then spatially normalised each movement to 100 equally spaced increments along the *Y*-axis, and calculated the average *X*-coordinate across the 100 samples, to produce a measure of average curvature in mm, where negative values represent leftward curvature and positive values rightward curvature. For Experiment 2, we extracted the same movement variables, except that RT was not relevant because the initiation of reaching was self-paced, and we additionally calculated the rate of correct flicker discrimination (DISCRIM) on no-jump trials.

For both experiments, our key dependent measure was Terminal Correction Rate (TCR) in jump trials. This is the percentage of trials that were deemed to be in a corrected position in the final frame of movement, by reference to reaching behaviour in no-jump trials. First, for each participant, for each attention condition, we grouped all no-jump trials, and calculated the mean and SD of the terminal angle (ANG). (For Experiment 2, no-jump trials with a flicker event were excluded from this calculation.) For each jump trial, we coded terminal correction status as 1 (i.e. corrected) if ANG fell more than 2.81 SDs from the no-jump mean, *in the direction of the jump*, and as zero if it did not. Each comparison thus approximates a one-tailed comparison at alpha 0.0025. This alpha was chosen, somewhat arbitrarily, to constrain type I error rate to 5% across the 20 jump trials per block in Experiment 2, and for consistency with prior studies in our group (e.g. McIntosh, Mulroue, & Brockmole, 2010; McIntosh et al., 2011); the same criterion was applied in Experiment 1 for cross-comparability between experiments. TCR was simply the average correction status multiplied by 100.

3. Results

3.1. Experiment 1 – SfP prior to reaching

A preliminary analysis was conducted for Experiment 1 to compare RTs between GO trials in which the unattended flanker was either congruent (plus) or incongruent (cross) with the attended flanker. Any influence of flanker congruence would indicate that participants were not able to attend exclusively to a single flanker location. For each participant, median RT was extracted for congruent and for incongruent GO trials separately for each side of attention (left, right); jump and no-jump trials were pooled for this analysis, because RT is measured prior to the target jump. A repeated-measures ANOVA by attention side and flanker congruence found no significant effects; average RT was closely similar between congruent and incongruent trials (499 vs. 501 ms; $p = 0.72$). Along with the low rate of reaching responses on NOGO trials (4.2%), this provides reassurance that participants were attending effectively to the instructed flanker.

The rates of terminal correction in jump trials were overall high. Indeed, they were at ceiling for 22 out of the 48 combinations of participant by condition. Given these ceiling effects, non-parametric analyses were used for this variable. A boxplot of median TCR for each condition is shown in Fig. 3a. In order to formally analyse the effect of SfP, the data for each participant were collapsed to two conditions, by taking the mean of the medians for jump trials to the attended side (mean of jump-left, attend-left and jump-right, attend-right) and the non-attended side (mean of jump-left, attend-right and jump-right, attend-left). A Wilcoxon signed rank test found no significant difference [$Z = 0.62$, $p = 0.53$], providing no indication that correction behaviour was either boosted or blunted toward the attended side.

For additional analyses of movement variables, the relatively few uncorrected jump trials were excluded. For descriptive purposes, we calculated the median movement endpoint in the *X* and *Y* dimensions for each participant in each target condition, and the group means of these values are plotted in Fig. 4a. Generally, participants reached short of the target, most so the left target, and least so for the right target. Two factors may have promoted this tendency. First, the task was performed without vision of the hand, or tactile feedback from targets, so visual-proprioceptive calibration of the working space was not possible. Second, the start button was 253 mm in front of the participant, and the target was 400 mm more distant, which was close to full stretch for some people. Participants might thus have tended to scale their reaches to their own comfortable reach distance, which would tend to be farthest on the right (ipsilateral) side, and least far on the left. Individually, whilst four participants reached on average further than the target (the farthest average reach for the middle target was 432 mm), the rest reached less than 350 mm. Fig. 4b shows sample trajectories for the participant with the shortest average reach, illustrating that, although the reaches were systematically short in the depth dimension, they were appropriately related to the horizontal position of the target, with movement corrections to the left and right locations emerging smoothly during the course of the reach.

In order to probe further for effects of side of attention, analyses of movement variables were conducted for no-jump and corrected jump trials. For each participant, median values were extracted for AMP, ANG, CURV, MT, PS and TPS, for each combination of attention side (left, right) and target location (left, middle and right). Medians were used as robust estimates of central tendency, per

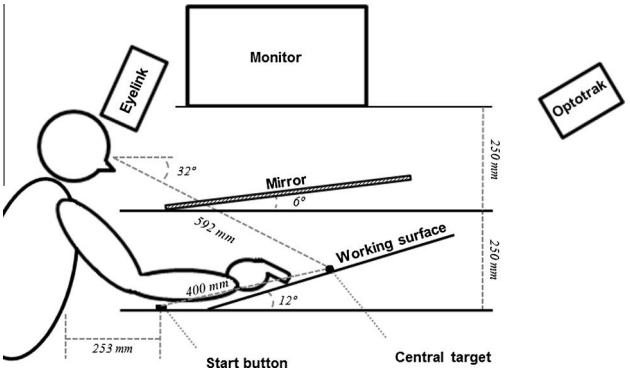

Fig. 1. Schematic diagram of the set up (not to scale, chinrest not shown). Stimuli were presented on a monitor and optically projected via a mirror to an inclined working surface in front of the participant. Solid lines indicate critical components of the apparatus; dashed lines are included to indicate measurements, and dotted lines to assign labels.

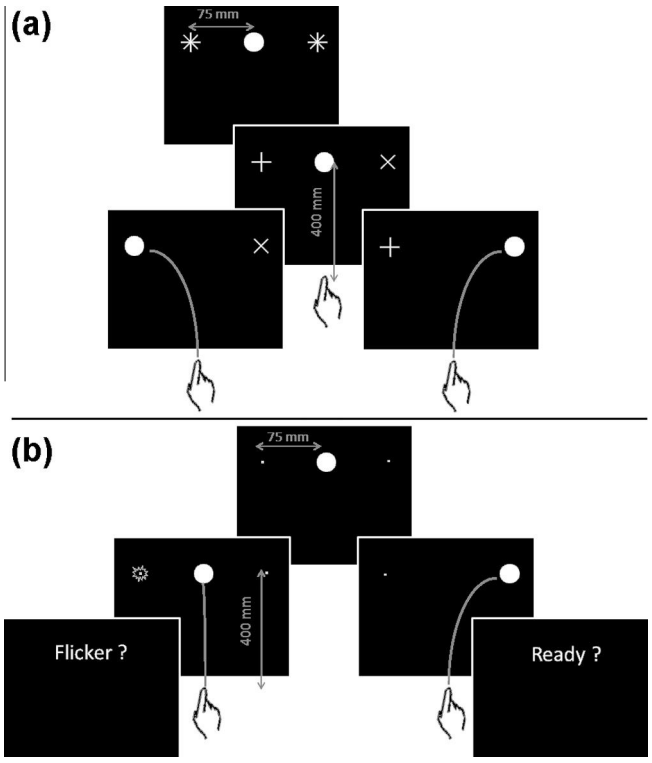

Fig. 2. (a) Experiment 1: schematic examples of the stimulus sequence for jump trials. In this example the participant initially fixates the central target, and attends covertly to the left flanking asterisk. After a random delay (750–1500 ms), this flanker turns into a plus sign, signalling for the participant to perform a pointing movement to the central target. At movement initiation, the central target jumps either to the attended side (left) or the non-attended side (right), and the participant must correct his or her movement online. (b) Experiment 2: schematic examples of the stimulus sequence for a no-jump trial with flicker (left branch) and a jump trial (right branch). The participant initially fixates the central target and attends covertly to the left flanking square. The reach is self-initiated, and the participant must monitor the attended flanker for a flicker at movement onset, which is present on half of no-jump trials. The flicker is a brief (20 ms) disappearance of the flanking square. Following the movement, the participant is asked to verbally report whether they detected a flicker. Jump trials were similar to Experiment 1, with the target jumping to one of the two flanking locations at button release. There is never a flicker on jump trials, and the participant must simply report when they are ready to begin the next trial.

participant, as few corrected jump trials were sometimes available. The group patterns are shown in Fig. 5. Separate repeated-measures ANOVAs found a significant effect of target location for every movement variable [all $F(2,22) \geqslant 11.37$, $p < 0.005$, $\eta_p^2 \geqslant 0.50$], but no significant main effect of attention [all $F(1,11) \leqslant 0.54$, $p \geqslant 0.47$], or interaction [all $F(2,22) \leqslant 1.04$, $p \geqslant 0.36$]. The pattern of responding to different locations can be seen in Fig. 5. Participants reached increasingly far for targets from left to right, consistent with a further comfortable stretch on the ipsilateral side. Because trajectory corrections toward the new target location unfolded during the reach (see examples in Fig. 4b), corrected reaches had a rightward CURV for left targets and a leftward CURV for right targets. Corrected reaches, especially those to the left, had extended MTs; and reaches to the right tended to reach a higher peak speed at a later time. Formal post hoc tests were not conducted, because no theoretically relevant effects of attention were involved.

Overall, then, Experiment 1 found no evidence for any influence of prior SfP upon immediately subsequent online correction. This result is, at best, inconclusive, because the task was rather easy for participants, and TCR was at ceiling in many cases, which could have obscured subtle effects of attention condition. Nonetheless, these generally high rates of correction will provide a useful baseline against which to compare performance during the more demanding concurrent SfP task introduced in Experiment 2.

3.2. Experiment 2 – SfP during reaching

Discrimination accuracy in the perceptual monitoring task of Experiment 2 was generally good, but well below ceiling (78% overall, where 50% is chance level, with no difference between flicker discrimination on the left and right: $t(11) = 0.71$, $p = 0.50$), confirming that participants attended to the monitoring task, and that it was a difficult one. Experiment 2 was designed for the reaching analyses to be restricted to no-flicker trials, in order to study the effects of SfP in the absence of any visual transient events preceding the target jump. Preliminary repeated-measures ANOVAs were conducted for each movement variable (median per condition per participant), to compare no-jump trials in which a flicker occurred against those in which it did not, with side of attention as an additional within-subjects factor. There were no significant effects involving side of attention, but flicker had a significant influence on MT [$F(1,11) = 30.46$, $p < 0.0005$, $\eta_p^2 = 0.74$] and on AMP [$F(1,11) = 6.32$, $p < 0.05$, $\eta_p^2 = 0.37$], with movements briefer (mean MT 374 vs. 389 ms) and of correspondingly reduced amplitude (mean AMP 263.3 vs. 267.8 mm) on flicker trials. These effects did not interact with the side of attention, so we interpret them as non-specific consequences of participants alerting to the flicker.

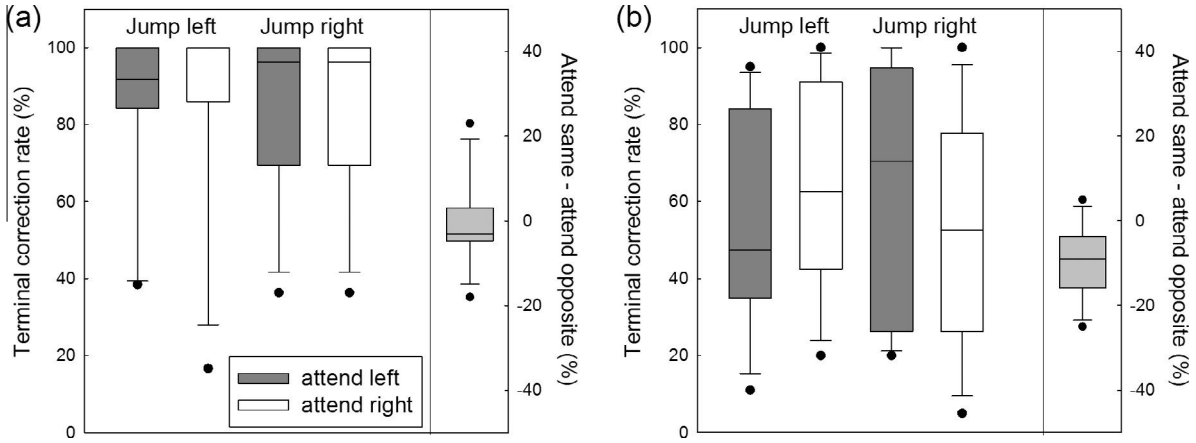

Fig. 3. (a) Experiment 1: the left section shows Terminal Correction Rate for the four combinations of jump side and attention side. The right section isolates the critical value for theoretical purposes, being the effect of side of attention (same or opposite side) on correction rate. Correction rates were subject to ceiling effects in Experiment 1, so boxplots are shown (horizontal lines are medians, boxes span 25th–75th percentiles, and whiskers span 10th–90th percentiles, with outliers shown). (b) Experiment 2: boxplot of Terminal Correction Rate, for comparability to Experiment 1 data in panel (a). An alternative, parametric plot of Experiment 2 Terminal Correction Rate is shown in Fig. 6c.

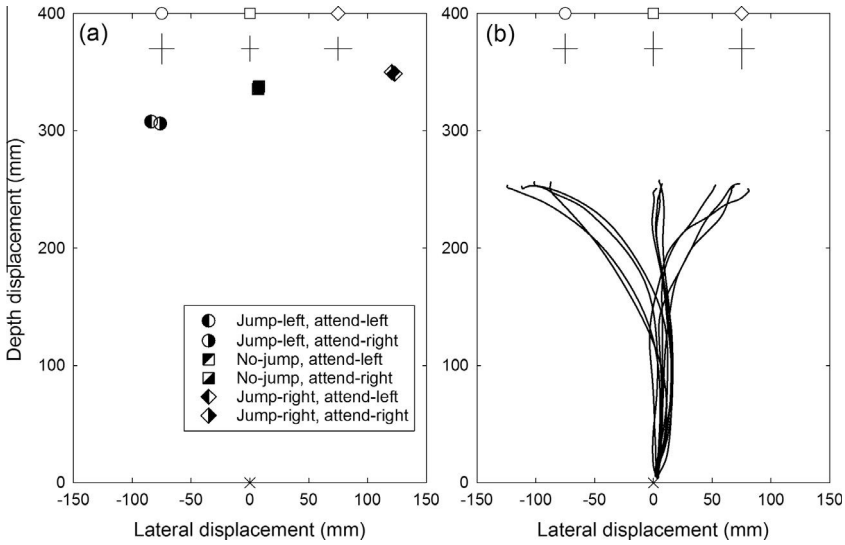

Fig. 4. (a) Experiment 1: aerial view of the workspace, showing average endpoints of the reaches made on no-jump and corrected jump trials, under the attend-left and attend-right conditions. Note that participants reached short of the true target positions, which are marked by the symbols at the top of the plots (circle is left target position, square is mid target position and diamond is right target position). Average within-subject IQRs in lateral and depth dimensions are indicated by the length of the horizontal and vertical arms of the crosses below each target. (b) Exemplar trajectories for the participant with the shortest average reach. Although the reaches were systematically short in the depth dimension, they were appropriately related to the horizontal position of the target, with movement corrections to the left and right locations emerging smoothly during the course of the reach.

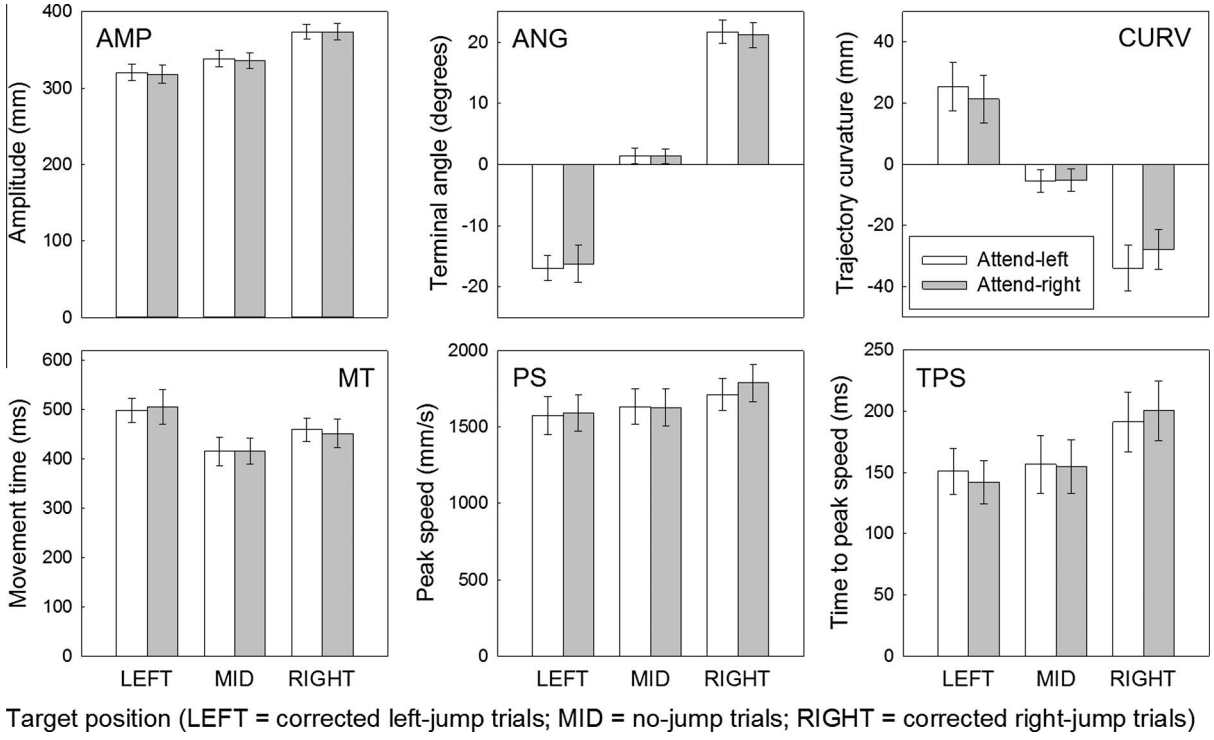

Fig. 5. Experiment 1: average movement variables for no-jump and corrected jump trials. Error bars represent the average within-subject IQRs.

These minor effects further justify the exclusion of flicker trials from other analyses.

The key measure, TCR, is represented as a boxplot in Fig. 3b, for direct comparison to the corresponding data from Experiment 1 (Fig. 3a). A Mann–Whitney test to compare the global correction rate (collapsed across conditions) between experiments confirmed a significant depression of TCR in Experiment 2 [$U = 27$, $p < 0.01$], indicating that the dual-task demand of lateralised visual monitoring reduced visuomotor responsiveness to the target jump. TCR data for Experiment 2 did not suffer ceiling effects, and are re-plotted parametrically in Fig. 6c. A repeated measures ANOVA by jump side (left, right) and attention side (left, right) found a significant interaction, reflecting relatively lower rates of correction toward the attended side [$F(1,11) = 16.41$, $p < 0.005$, $\eta_p^2 = 0.60$]. The critical difference, between TCR for corrections to the attended and unattended side, is depicted in the right portion of Fig. 6c.

Fig. 6a shows a descriptive plot of the group mean of median movement endpoints for no-jump and corrected jump trials. As

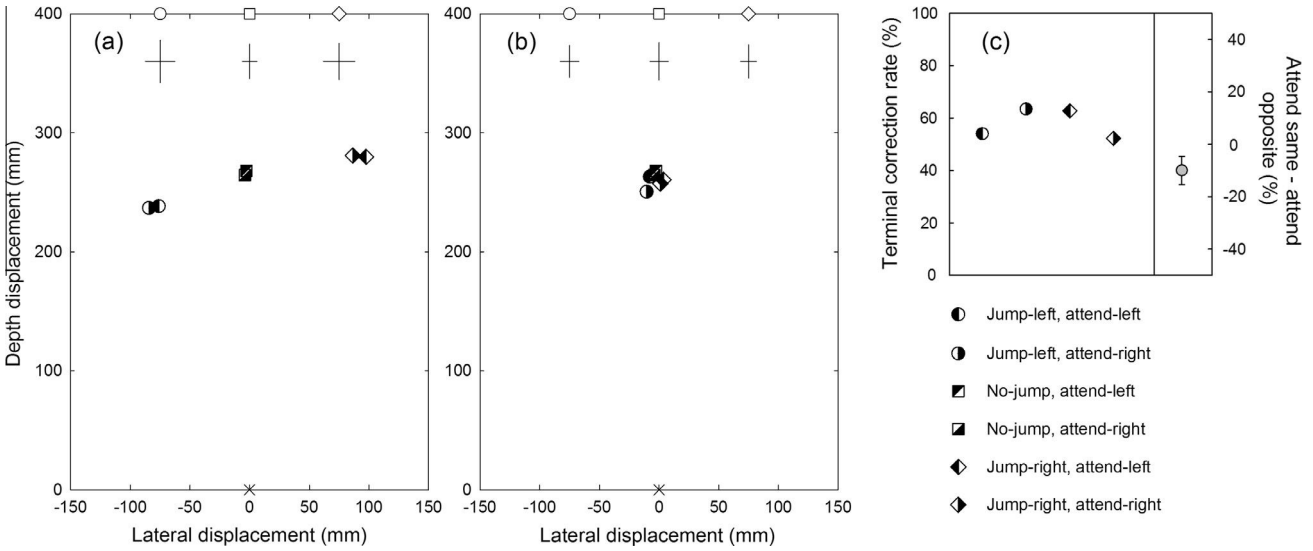

Fig. 6. Experiment 2: aerial view of the workspace, showing average endpoints of the reaches made on no-jump and corrected jump trials, under the attend-left and attend-right conditions. Separate plots are shown for those jump trials that were classed as corrected (a) and as uncorrected (b); the no-jump data are the same in panels (a) and (b). Note that participants reached substantially short of the true target positions, which are marked by the unfilled symbols at the top of the plots (circle is left target position, square is mid target position and diamond is right target position). The average within-subject IQRs in lateral and depth dimensions are indicated by the length of the horizontal and vertical arms of the crosses below each target. Panels (a) and (b) show that the side of attention had relatively little influence on the spatial extent of reach correction to the left or right. Panel (c) indicates that attention had a significant influence on whether a reach correction was made at all. The left section of panel (c) shows TCR in the four combinations of jump side and attention side; the right section isolates the effect of side of attention (same or opposite side) (±95% CI), confirming a reduced rate of reach correction to the attended side.

in Experiment 1, participants reached short of the true target location, most severely for the left target, and least so to the right target. For completeness, average endpoints of uncorrected jump trials are plotted in Fig. 6b; but there were generally low numbers of uncorrected trials (two participants had no uncorrected trials in at least one condition), and these trials were not analysed further. Analyses of movement variables were conducted for no-jump and corrected jump trials, exactly as for Experiment 1, and quite similar patterns were obtained (Fig. 7). Separate repeated-measures ANOVAs found a significant effect of target location for every variable [all $F(2,22) \geqslant 8.71$, $p < 0.01$, $\eta_p^2 \geqslant 0.44$], except for PS. As before, the side of attention had no significant effect [all $F(1,11) \leqslant 0.31$, $p \geqslant 0.59$] or interaction [all $F(2,22) \leqslant 1.93$, $p \geqslant 0.18$] for any variable. This supplementary analysis of the kinematic character of reach corrections is not high-powered, given the limited numbers of jump trials available. However, it suggests that the effects of SfP are principally on the likelihood of making a correction to one or other side; these corrections, once initiated, unfold quite similarly, regardless of the location of SfP.

4. Discussion

Across two experiments, we investigated whether perceptual attention constrains the online control of reaching. In Experiment 1, perceptual discrimination immediately preceded the reaching task. In Experiment 2, the perceptual demand was concurrent with reach execution. We did not see effects of perceptual attention on no-jump trials, in which the reach target did not jump. This lack of influence on no-jump trials was expected, because every reach was directed initially to the same central target position, and highly predictable manual responses are often resistant to attentional distraction (McIntosh & Buonocore, 2012; Tipper, Howard, & Jackson, 1997). Instead, our interest was in the rates of online correction for reaches during which the target jumped toward or away from the attended side. According to Milner and Goodale (2008), the planning of a visually-guided reach may involve perceptual selection of the target but, once underway, its online control is an autonomous function of the visuomotor system. Thus, if SfA is dissociable from SfP, online correction is an ideal candidate behaviour in which to demonstrate the dissociation (Liu, Chua, & Enns, 2008; Schenk et al., 2005).

Experiment 1 did not show any effect of prior SfP on online correction. Superficially, this suggests that online control can indeed dissociate from perceptual attention, consistent with the findings of Liu, Chua, and Enns (2008). However, Experiment 1 cannot be considered a strong test of the relation between SfP and SfA, because correction rates were at or close to ceiling level in all conditions. This confirms that online correction is highly efficient, but it provides scant basis for probing differences in correction efficiency between conditions. An alternative or additional explanation for the failure to find an influence of prior SfP in Experiment 1 might be that the perceptual task did not overlap in time with reach execution. This may have enabled the participant to perform the perceptual and visuomotor tasks in sequence, disengaging perceptual attention from the lateralised stimulus before initiating the reach. Nonetheless, Experiment 1 serves a useful purpose, because it demonstrates normally responsive online correction behaviour for the reaching stimuli used here, and thus provides a baseline against which to compare online correction rates in Experiment 2, in which the perceptual task did overlap in time with reach execution.

The first striking aspect of online correction rates in Experiment 2 was that they were globally depressed by comparison to Experiment 1, with only 58% of jump trials on average triggering corrections. This indicates that perceptual attention to a stimulus other than the initial reach target disrupts the ability to make online corrections. It is important to note that this disruption was caused by the endogenous monitoring itself, not by the flicker event that was monitored for, as this never occurred in the jump trials in which corrections were studied. This refutes the conclusions of Liu, Chua, and Enns (2008), who reported no effect of a perceptual monitoring task on online reach correction. As noted in the Introduction, there may be at least two artefactual explanations for Liu et al.'s null finding. First, their perceptual stimulus involved

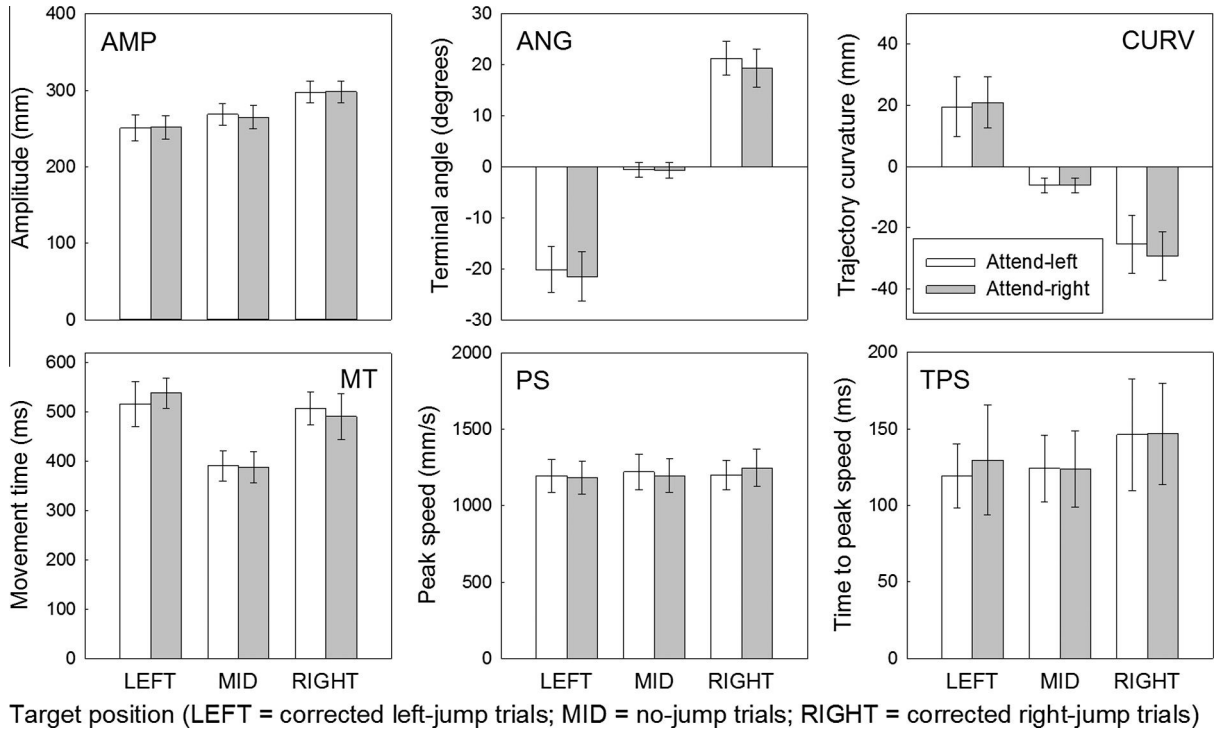

Fig. 7. Experiment 2: average movement variables for no-jump and corrected jump trials. Error bars represent the average within-subject IQRs.

exogenous visual changes, in both dual and single-task conditions, which may have tended to make attentional allocation similar between conditions. Second, and more crucially, their perceptual task was performed in central vision and was rather easy, with average accuracy higher than 95%, so may have spared sufficient attentional resources to support online correction. By contrast, our own perceptual monitoring task was presented away from fixation, and was performed with an average accuracy of 78% (where 50% is chance level), suggesting that it was more challenging. This dual-task interference contrasts with the finding that a demanding *auditory* task does not impair visually-based online reach corrections (McIntosh, Mulroue, & Brockmole, 2010), implying that it is due specifically to the perceptual task loading on the same visual attention resource as online correction, and not to some more general attentional or executive resource limitation (see also Hesse & Deubel, 2011; Hesse, Schenk, & Deubel, 2012).

The demonstration of global perceptual interference with online correction confirms a degree of dependence of SfA on SfP. But Experiment 2 additionally showed a specific directional influence of SfP, such that corrections were least likely to be directed to the monitored location, and *relatively* more likely to go to the opposite side. This inhibitory effect of attention is reminiscent of the trajectory deviations observed for reaching movements (e.g. Gangitano, Daprati, & Gentilucci, 1998; Howard & Tipper, 1997; Tipper, Howard, & Jackson, 1997) and saccades (Doyle & Walker, 2001; Godijn & Theeuwes, 2004; Ludwig & Gilchrist, 2003; McSorley, Haggard, & Walker, 2004; Sheliga, Riggio, & Rizzolatti, 1995) under conditions in which top-down factors, such as distractor predictability, give participants scope to actively inhibit the distractor location. In Experiment 2, relevant top-down knowledge was *always* available, because participants were instructed which side to monitor for the perceptual change. Within a vector-based action coding framework, the inhibition effect can be taken as evidence that allocating SfP automatically primes an action to the attended location. In order to reach to the central target, the participant must actively inhibit the primed flanker location in the relevant motor map, and this inhibition is revealed by a reduced likelihood of online correction if the target subsequently jumps to that location; though, once a correction is actually implemented, its kinematic character and extent do not much differ as a function of SfP.

When considered alongside prior literature showing that SfA constrains SfP, our findings indicate that the relationship is reciprocal: SfP constrains SfA, even for an automatic visuomotor behaviour such as online correction. Previous studies have shown biasing of manual responses away from attended locations, but these effects have always been interpretable as a suppression of the primed action plan once attention has left that location. Our Experiment 2 adds unique value in two ways: first, by showing inhibitory effects of a purely endogenous perceptual task on reaching, as previously done for the saccadic system by Sheliga, Riggio, and Rizzolatti (1995); second, by showing that these effects can be *concurrent* with ongoing perceptual prioritisation of the same location. At first sight, a reciprocal yoking of attention between perception and action may seem equally consistent with the VAM (Schneider, 1995) and the premotor theory (Rizzolatti et al., 1987). On closer consideration, our particular findings may be problematic for the premotor theory. According to this theory, SfP is identical with SfA, depending directly upon activation within the same pragmatic maps, so to inhibit an action plan to any location would simultaneously prevent perceptual monitoring of that location. Without adding further assumptions, such as inhibition at motor output stages, the premotor theory cannot explain how our participants could suppress actions to a location, whilst simultaneously performing a difficult perceptual monitoring task there.

On the other hand, the VAM can accommodate these findings with relative ease, because this model does not assume any co-dependence of perceptual and motor representations beyond an initial shared mechanism of visual selection. According to the VAM, perceptual attention to the monitored location would initially prime action responses to the same location, because of this shared selection mechanism, but top-down inhibition could be

applied subsequently to the primed location within the relevant pragmatic maps of the action system, without any parallel diminution of the corresponding perceptual representation. This flexibility within the VAM also makes it possible to imagine that awareness for one side of space could be impaired at a relatively late stage of perceptual processing, without compromising visuomotor responsiveness to the same locations, potentially allowing for neuropsychological dissociations of action from awareness (e.g. McIntosh et al., 2004, 2005; Milner & McIntosh, 2005; Schenk et al., 2005).

The present experiments provide clear evidence that SfP constrains SfA during ongoing visually-guided action, consistent with evidence from Hesse and colleagues (Hesse & Deubel, 2011; Hesse, Schenk, & Deubel, 2012), and refuting the idea of independent selection mechanisms for perception and action (Liu, Chua, & Enns, 2008). Allocating attention endogenously for the purposes of perceptual monitoring grossly reduces online correction behaviour, and corrections are least likely to be triggered toward the attended location. This inhibition of action at the focus of perceptual attention echoes the known influence of exogenous distractors on reaching trajectories, and implies top-down inhibition of actions primed automatically toward the attended location. The priming and subsequent inhibition of actions to a location attended purely for perceptual discrimination is broadly consistent with both the VAM (Schneider, 1995) and the premotor theory (Rizzolatti et al., 1987). Crucially, however, the inhibition of corrections to the attended location that we observed was *concurrent* with successful perceptual monitoring at that location. This wholly novel pattern implies a high degree of independent control over action representations, subsequent to initial target selection, and favours the VAM over a premotor account.

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